BNL BLIP Irradiation Experiment Planning

RaDiATE Collaboration

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BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science

U.S. DEPARTMENT OF ENERGY

Irradiation Facilities

- **Brookhaven Linear Isotope Producer (BLIP)**
- **Tandem van de GRAAFF**

PIE Facilities

- **Isotope Extraction and Processing PIE Facility**
- **Synchrotron**
- **CFN**

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BNL Irradiation and Post-Irradiation Facilities

BLIP: Irradiation studies using

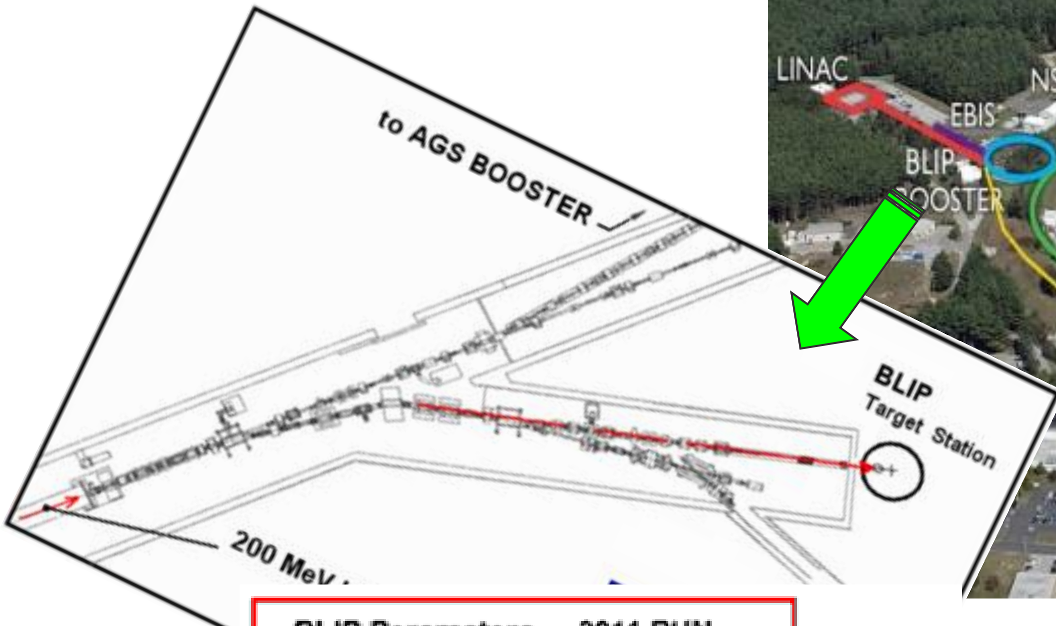
(a) high energy protons (66 MeV to 200 MeV) and
(b) spallation neutrons from 118 MeV protons on target. Materials for fusion and fission reactors as well as high power accelerators (LHC, LBNE, etc.)

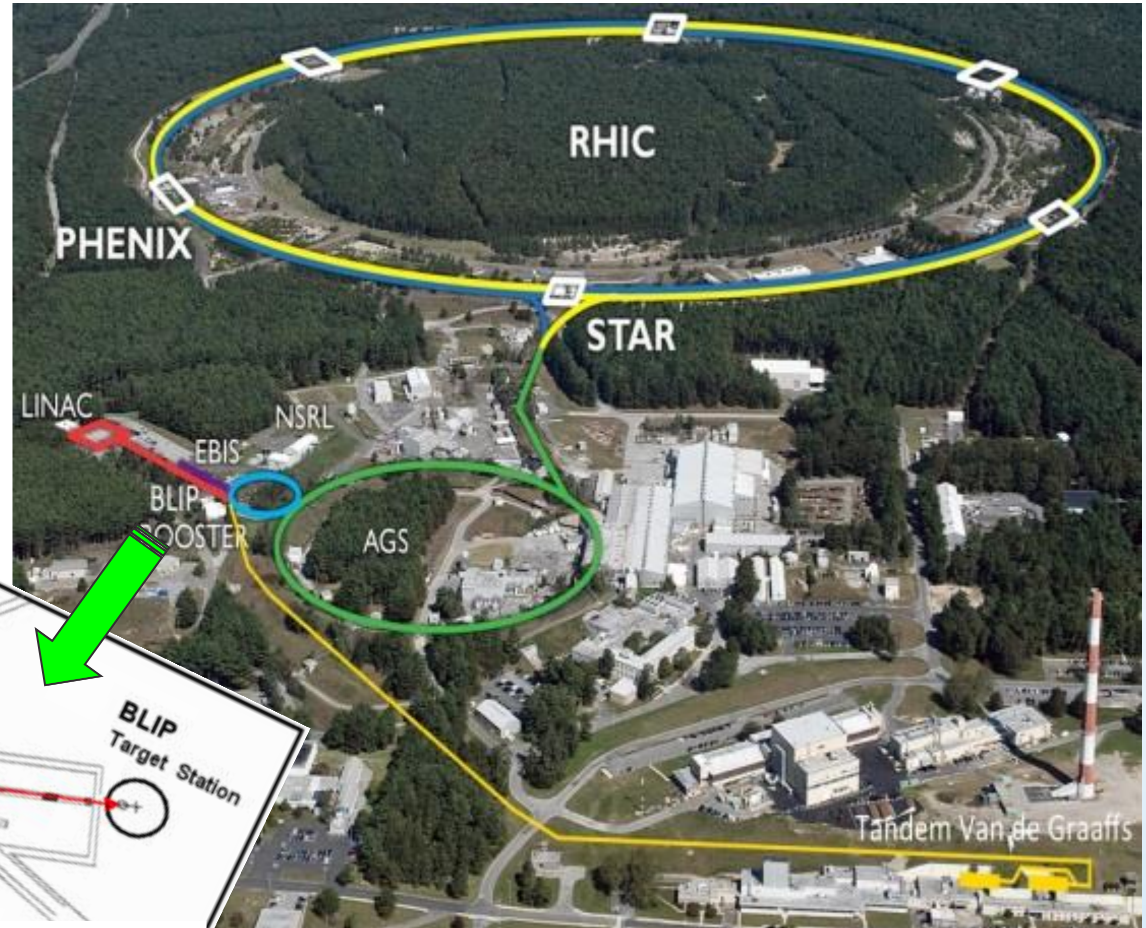
Tandem Van de Graaff: Irradiation facility with 28 MeV protons or ions from an ion array up to ^{197}Au

Isotope Extraction-Processing Facility:
An experimental area in the facility hot cells for complete macroscopic analysis of irradiated samples

NSLS/NSLS II Synchrotrons – X-ray diffraction

BLIP - Working Horse of Accelerator-based Irradiations





BLIP Parameters		2011 RUN
Rep Rate	=	6.67 Hz
Pulse Length	=	440 micro-secs
Micropulse length	=	5 ns
Micropulse structure	=	200.25 MHz
Average Current*	=	~106 micro-A
6 sigma beam within	=	2-inch diameter
Beam Gaussian	==>	1 sigma = 4.233 mm

Projected current in 2016 Run = 140uA !!

Materials linked with:

Neutrino Factory, LHC, LBNE, Next Gen Fusion/fission Reactors

Materials:

Steels, Inconel, S-Invar, Gum Metal, Ti-6Al-4V, Cu, Glidcop, W, Ta
Graphite (s), C/C composites, SiC/SiC
Mo, Mo-GR, Cu-CD
Interfaces (Cu-Ti-Graphite, Al_2O_3-Ti6Al4V

Facilities Utilized/integrated:

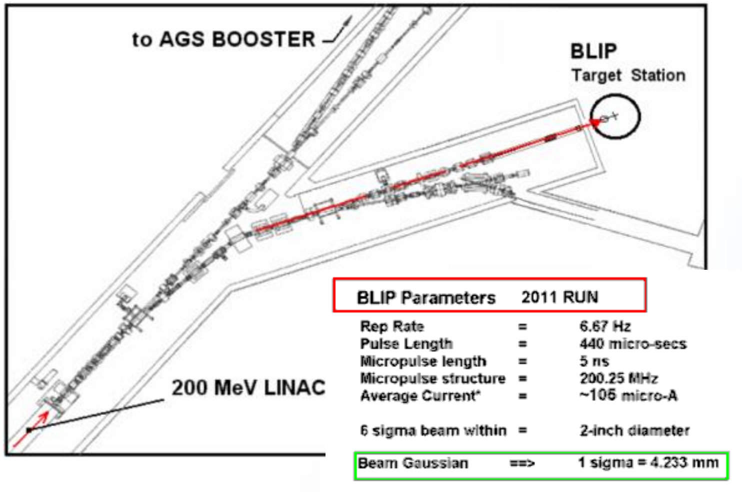
200 MeV BNL Linac/BLIP, Tandem, Isotope Extraction Facility
National Synchrotron Light Source (NSLS) and NSLS II
Center of Functional Nanomaterials

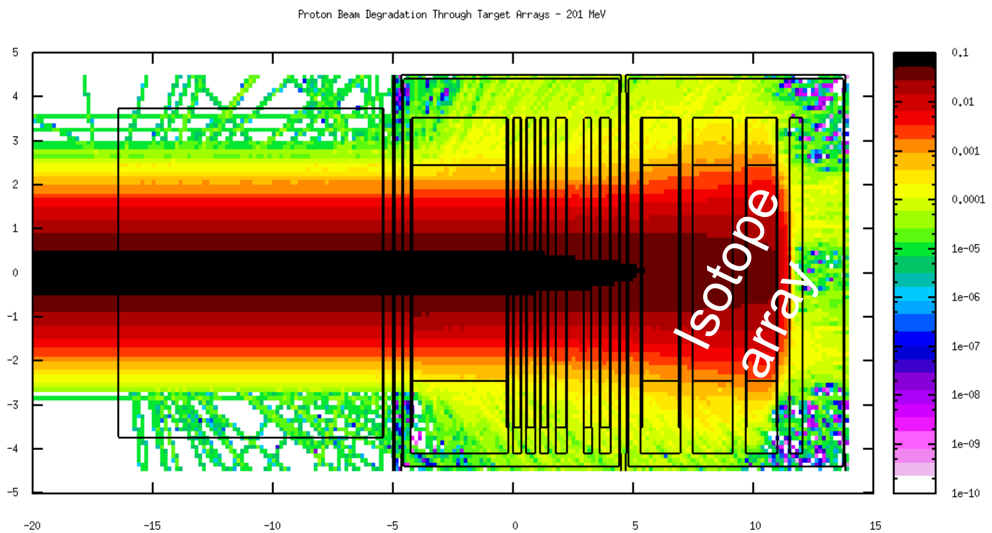
High Energy Proton Irradiation

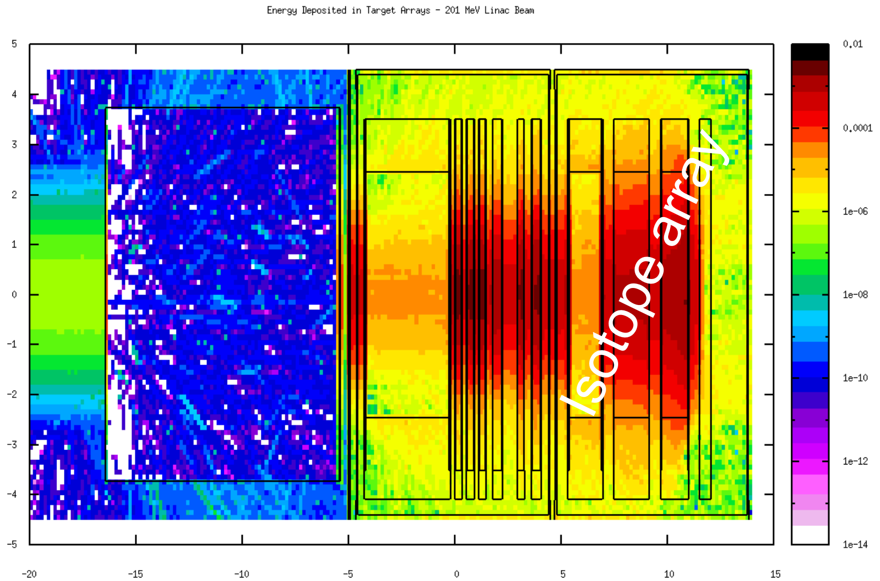
(energies up to 200 MeV)

Material Irradiation Damage Studies for:

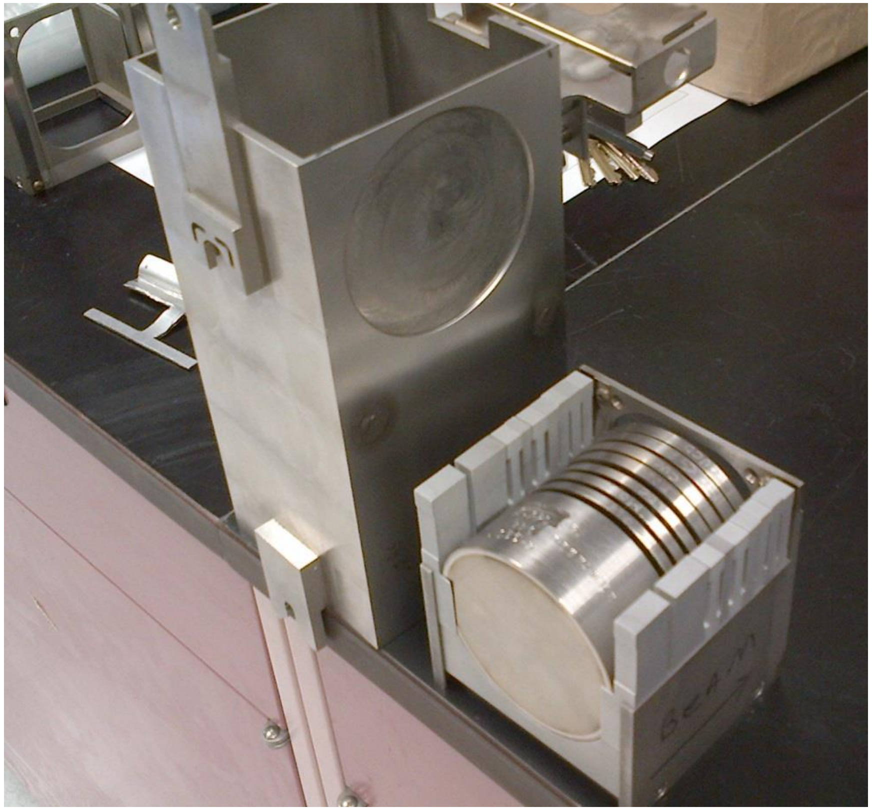
- Large Hadron Collider (CERN)
- Long Baseline Neutrino Experiment
- Neutrino Factory
- FRIB

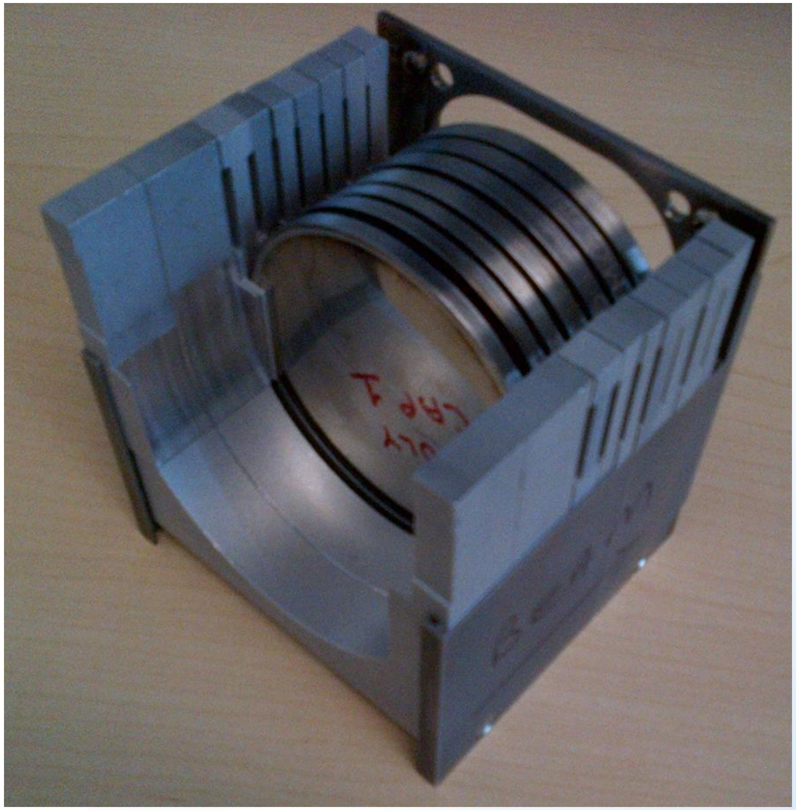




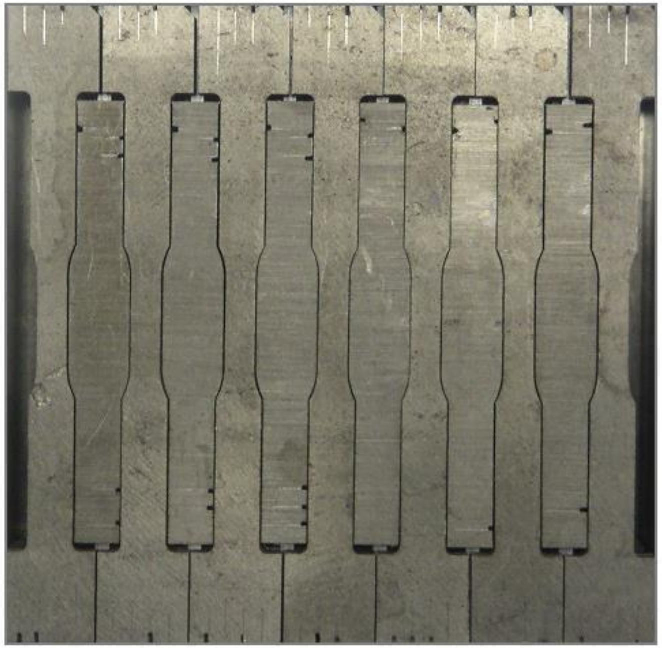


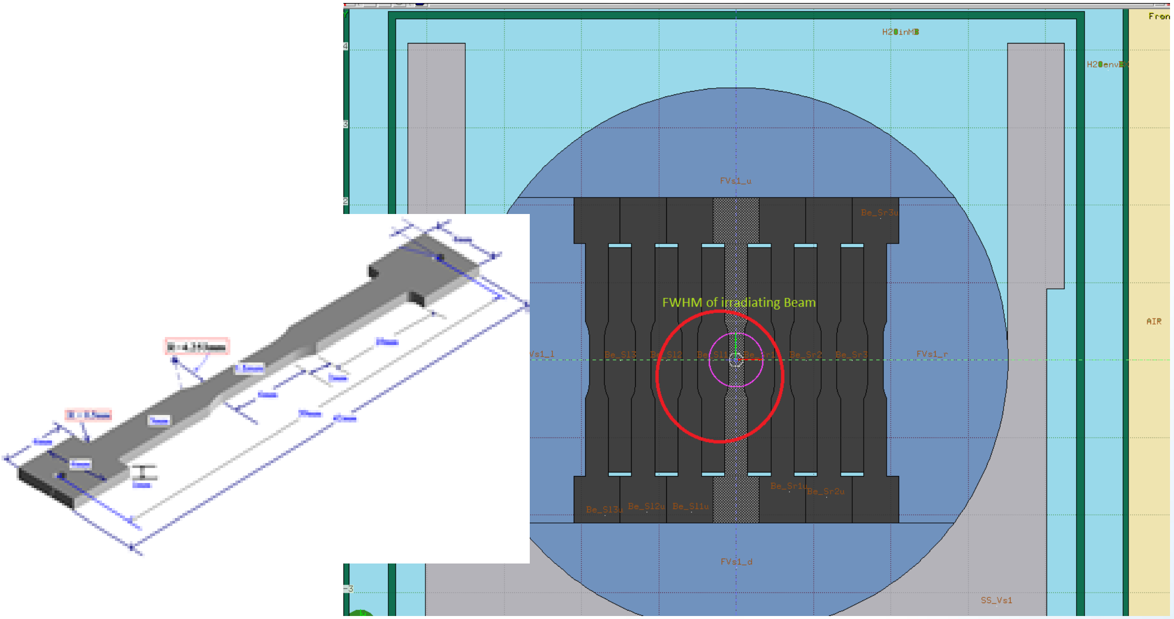
Proton Irradiation

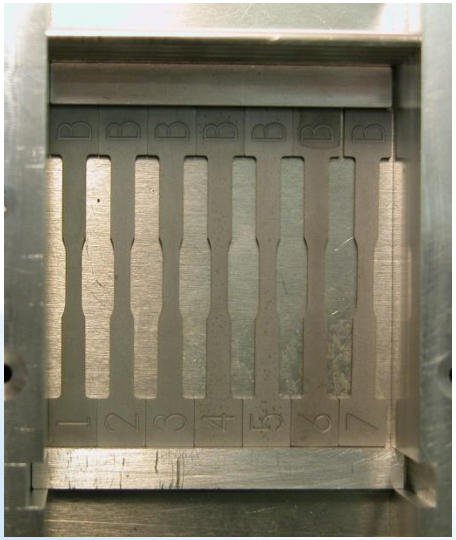


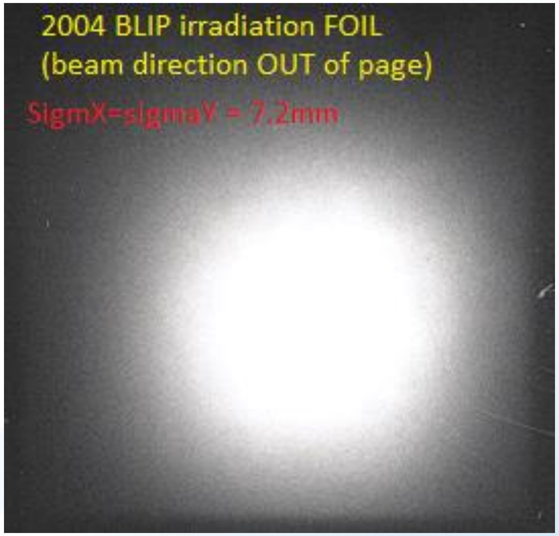


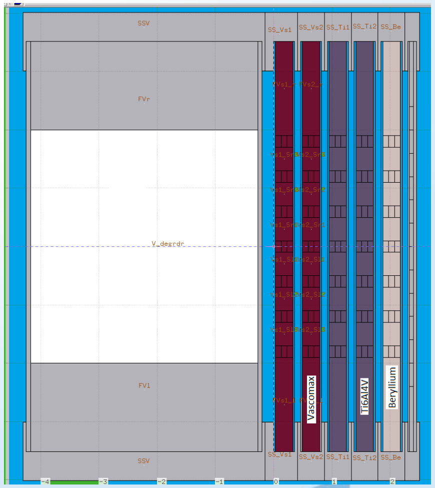
Proton Irradiation

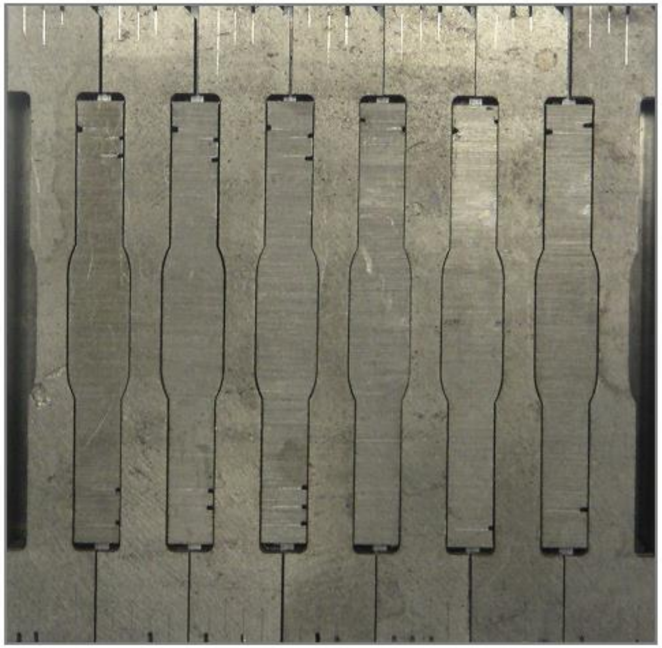


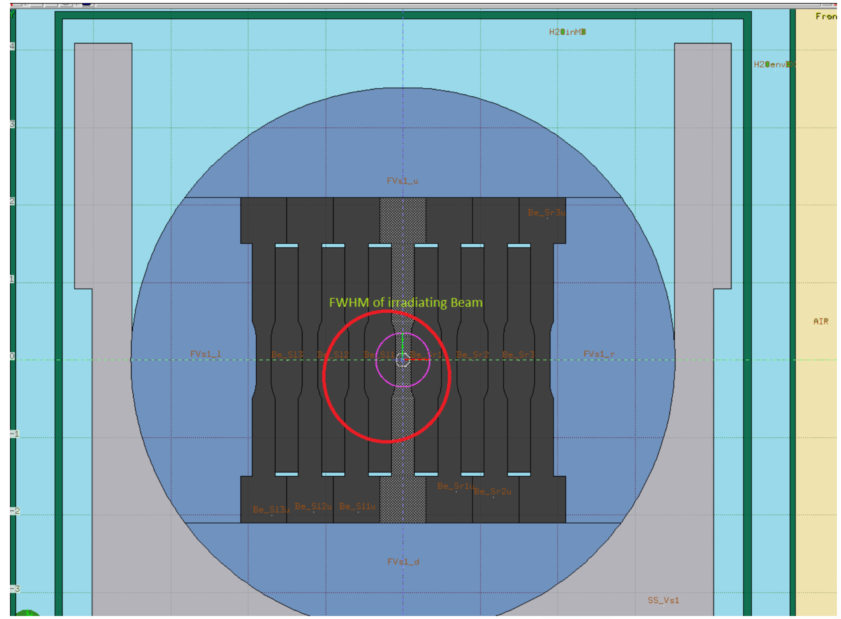




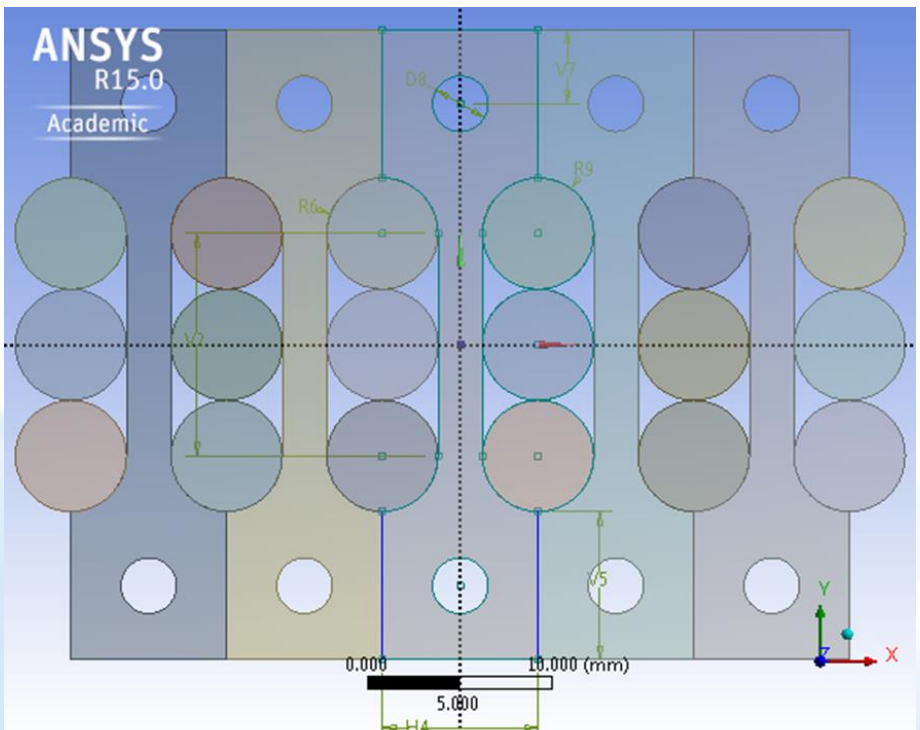




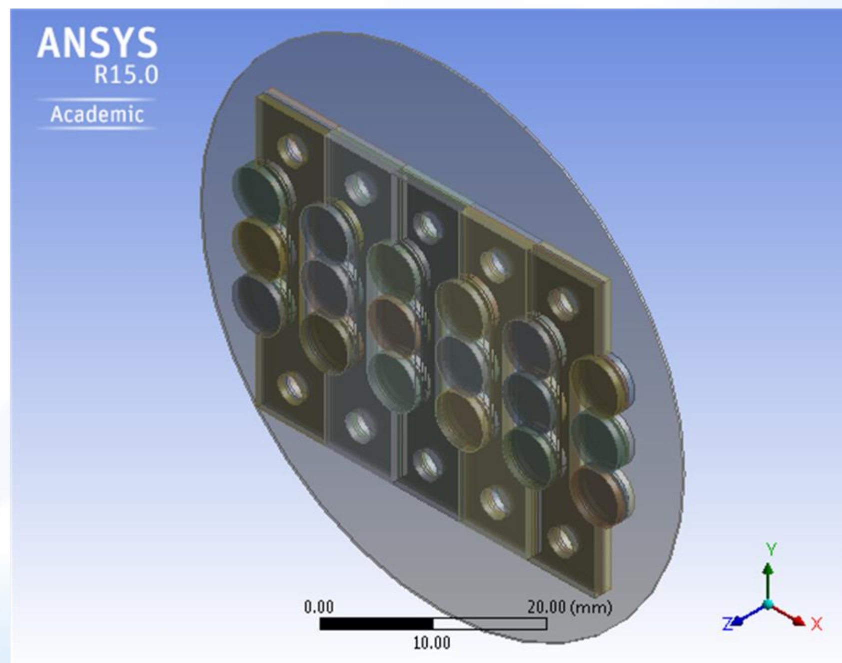




FWHM of irradiating Beam
AIR

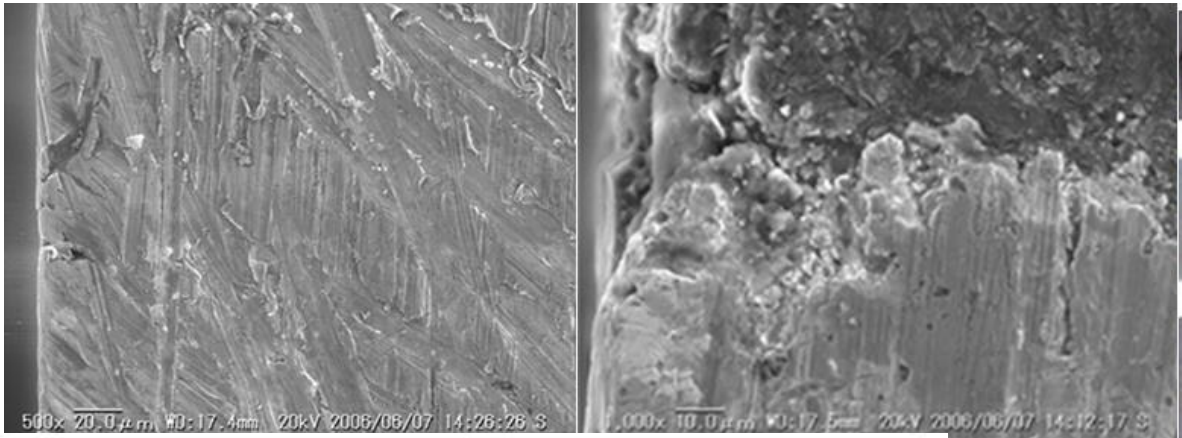


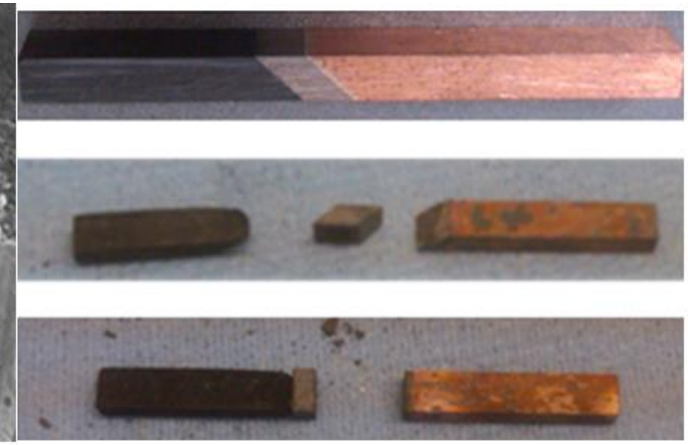
ANSYS
R15.0
Academic
D8
V7
R9
R6
V5
0.000
10.000 (mm)
5.000
H4
Y
X

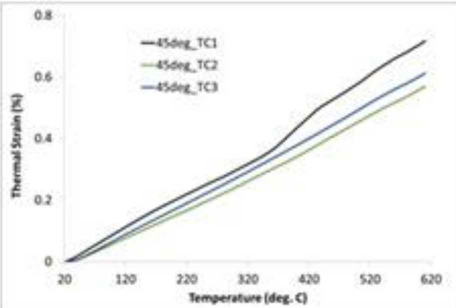


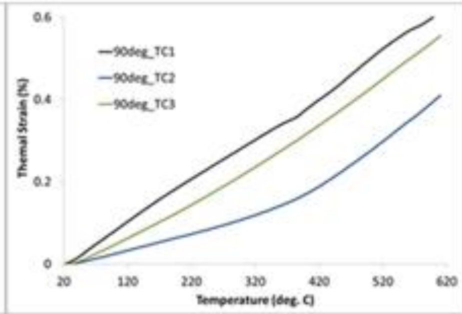
ANSYS
R15.0
Academic
0.00
20.00 (mm)
10.00
Y
Z
X

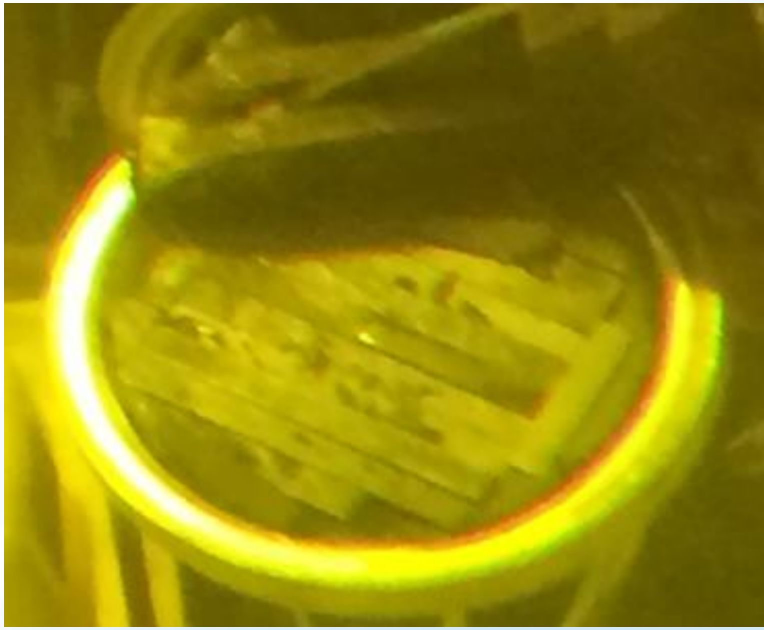
200 MeV Proton Irradiation

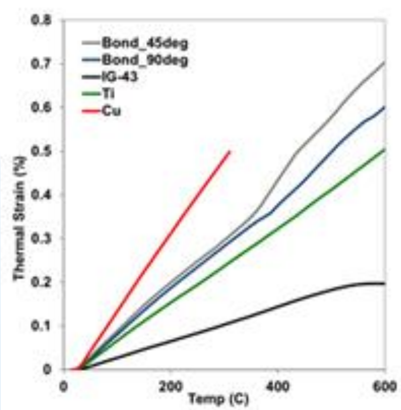


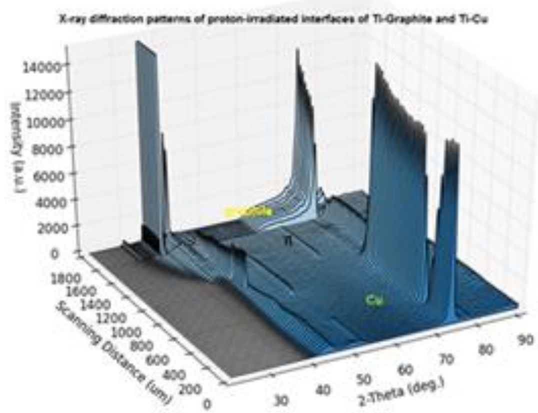


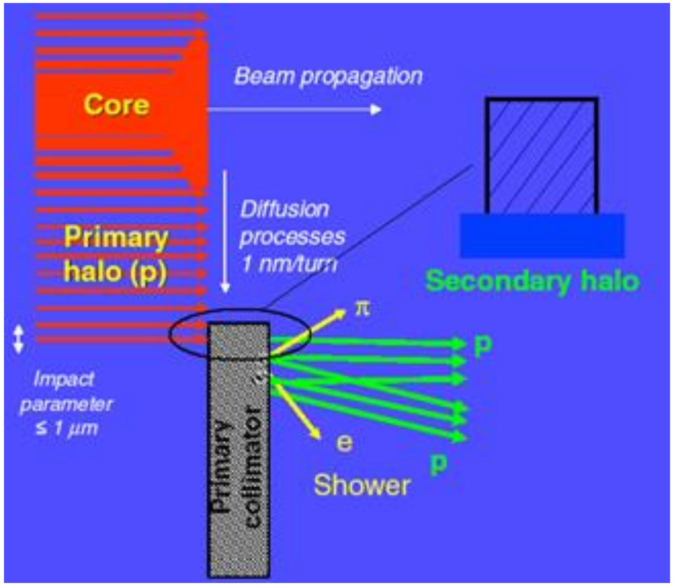


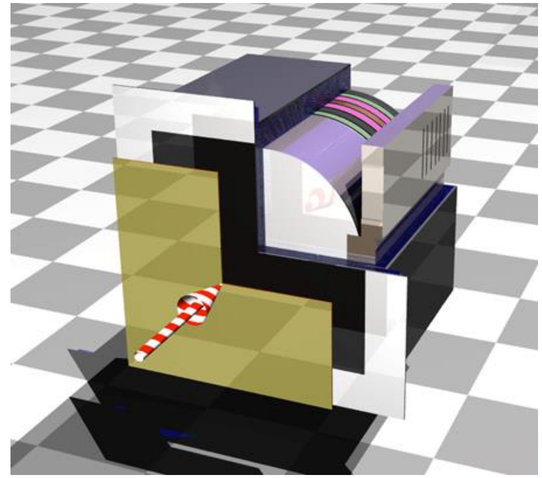


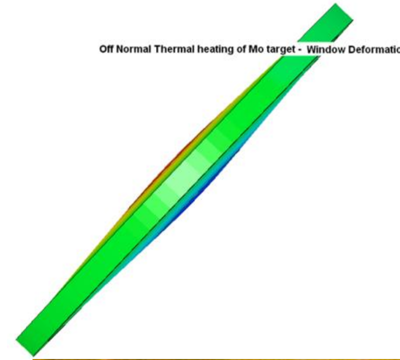


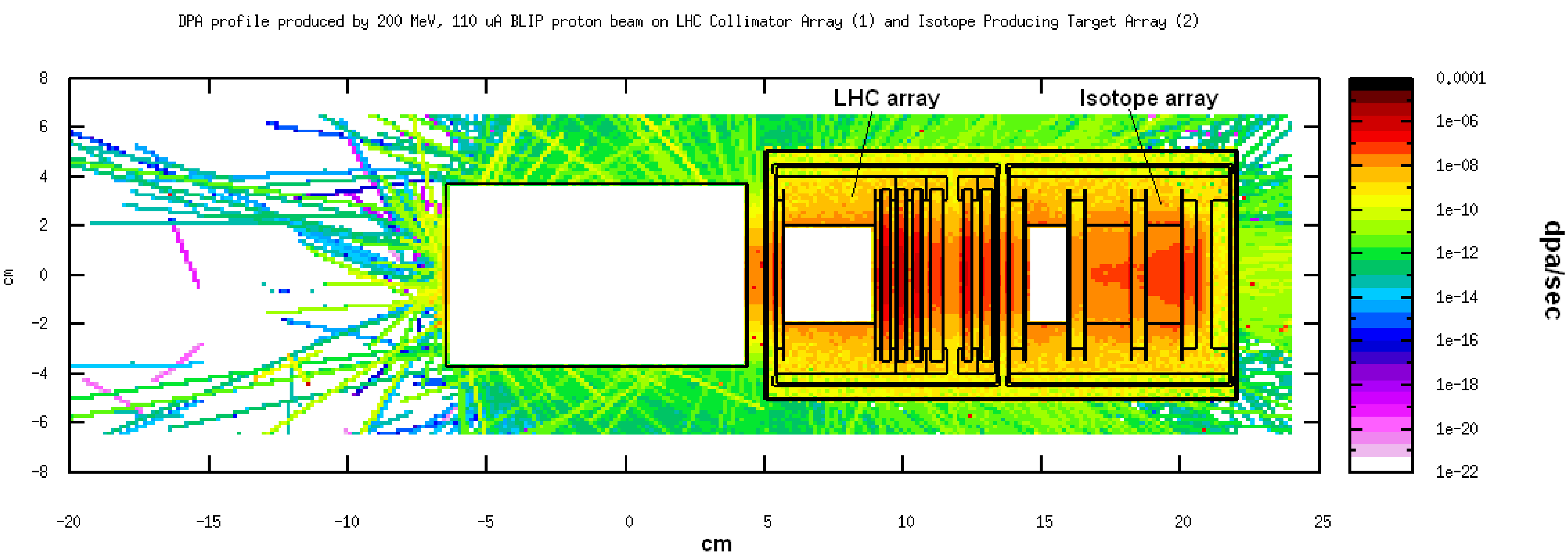




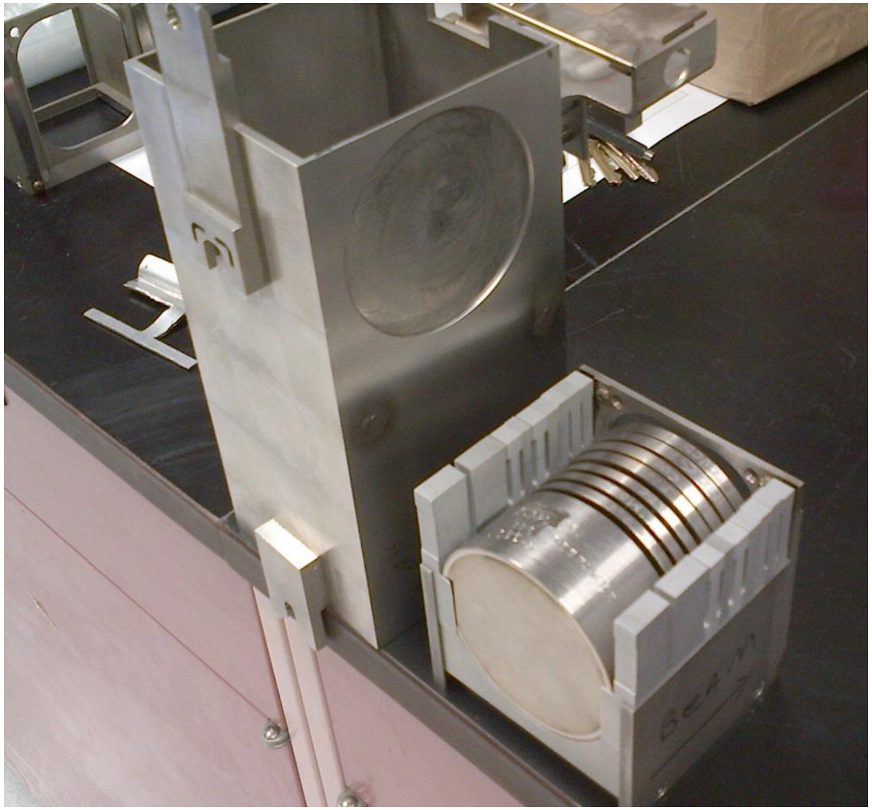

Core
Beam propagation
Diffusion processes 1 nm/turn
Primary halo (p)
Secondary halo
Impact parameter ≤ 1 μm
Primary collimator
π
p
e
Shower
p

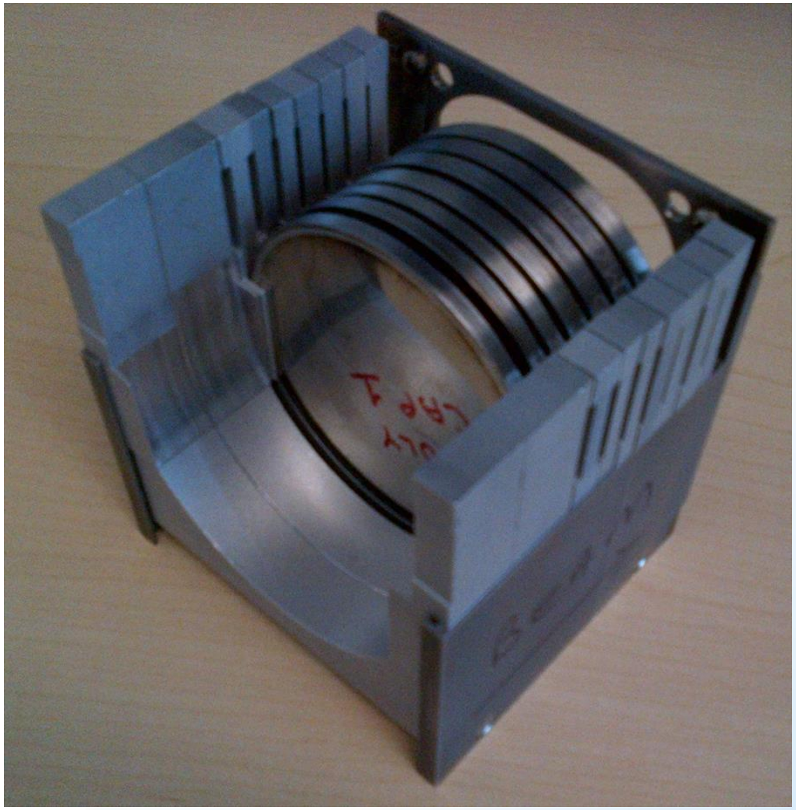



Off Normal Thermal heating of Mo target - Window Deformation

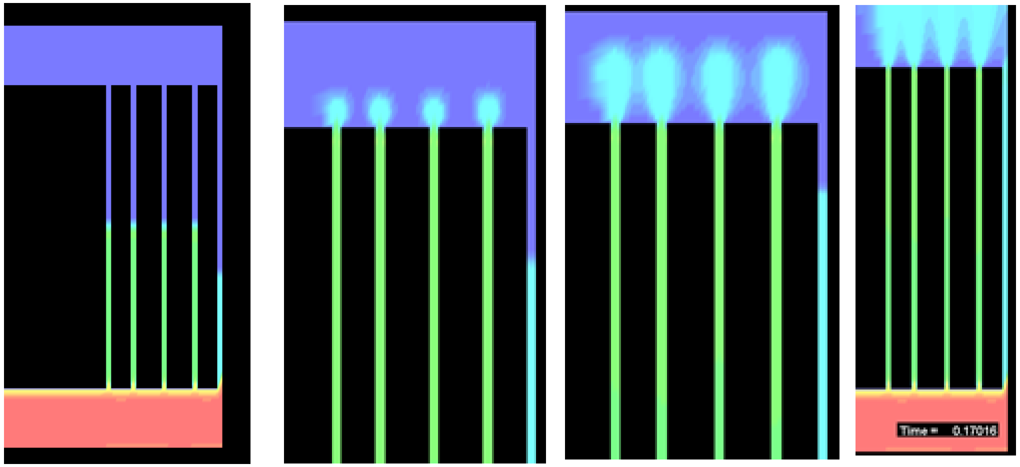

DPA profile produced by 200 MeV, 110 uA BLIP proton beam on LHC Collimator Array (1) and Isotope Producing Target Array (2)
LHC array
Isotope array
cm
cm
dpa/sec
0.0001
1e-06
1e-08
1e-10
1e-12
1e-14
1e-16
1e-18
1e-20
1e-22

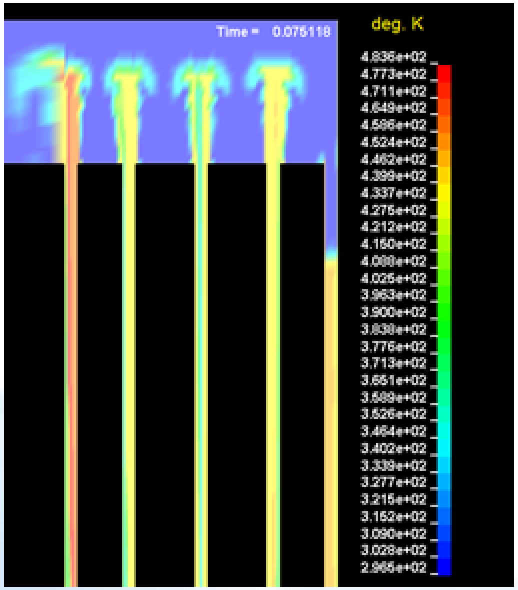
Proton Irradiation

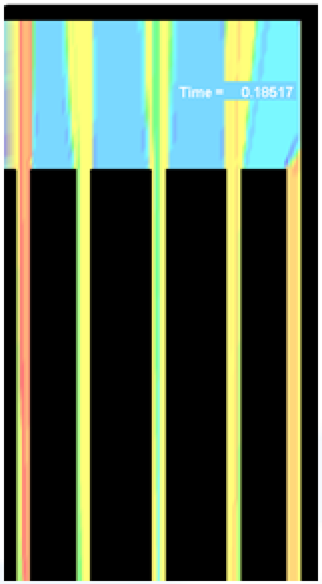


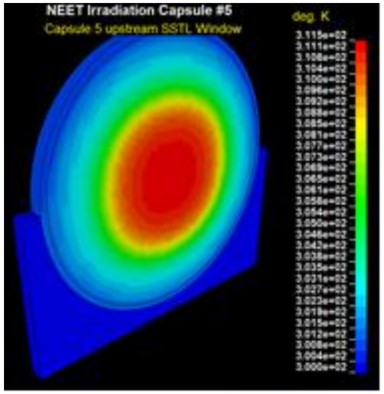


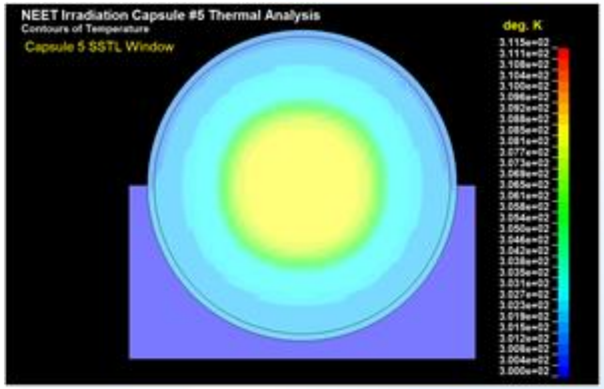
Thermo-mechanical Analyses Supporting Proton Irradiation

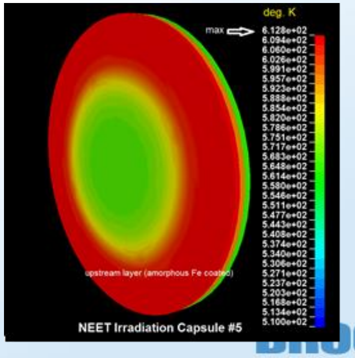




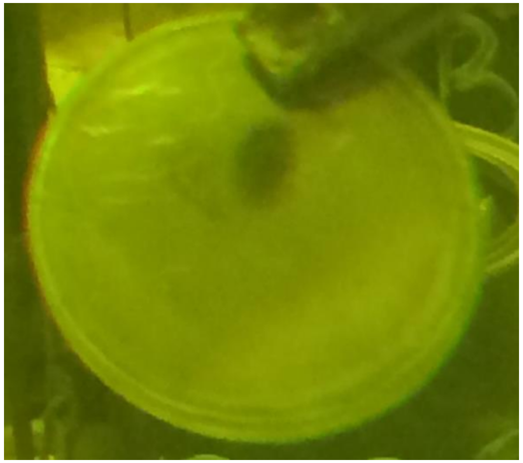


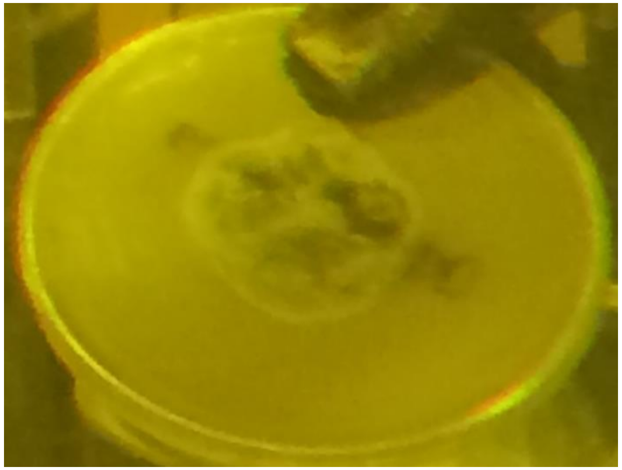


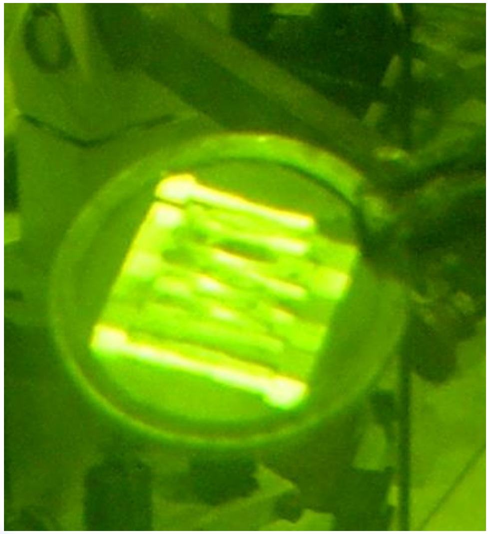


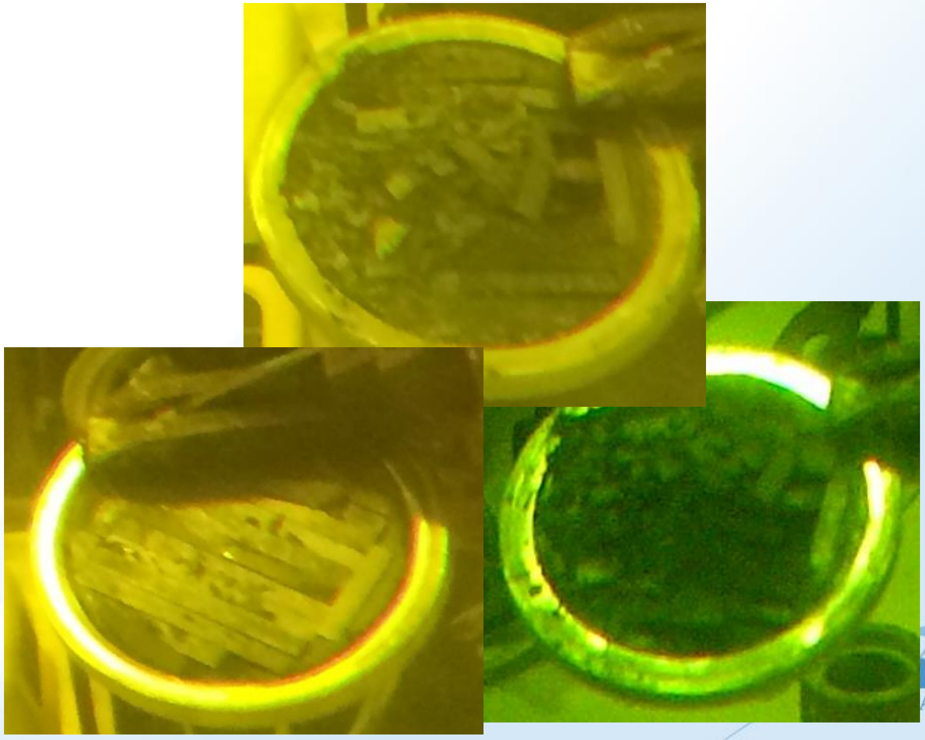


Proton Irradiation

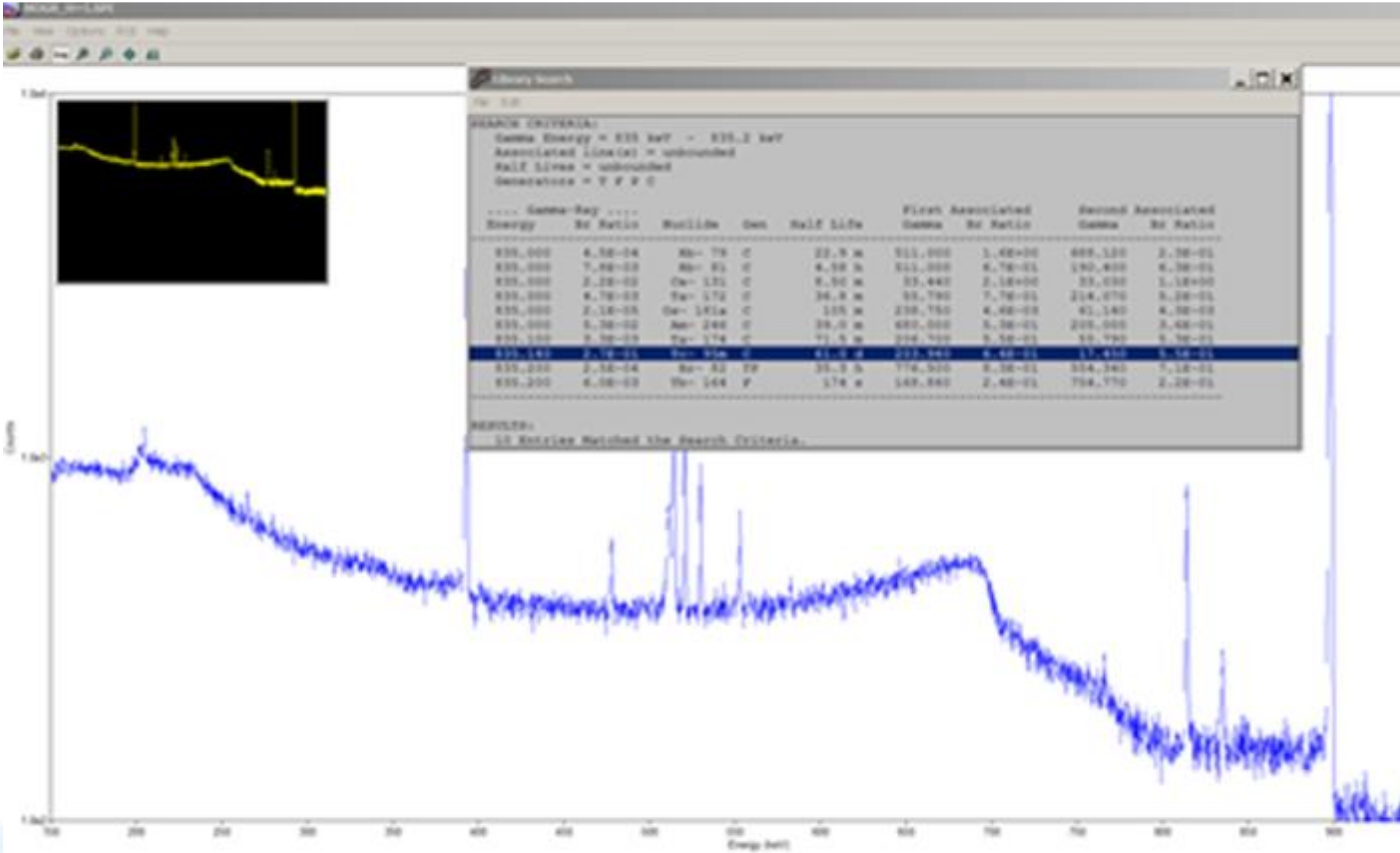




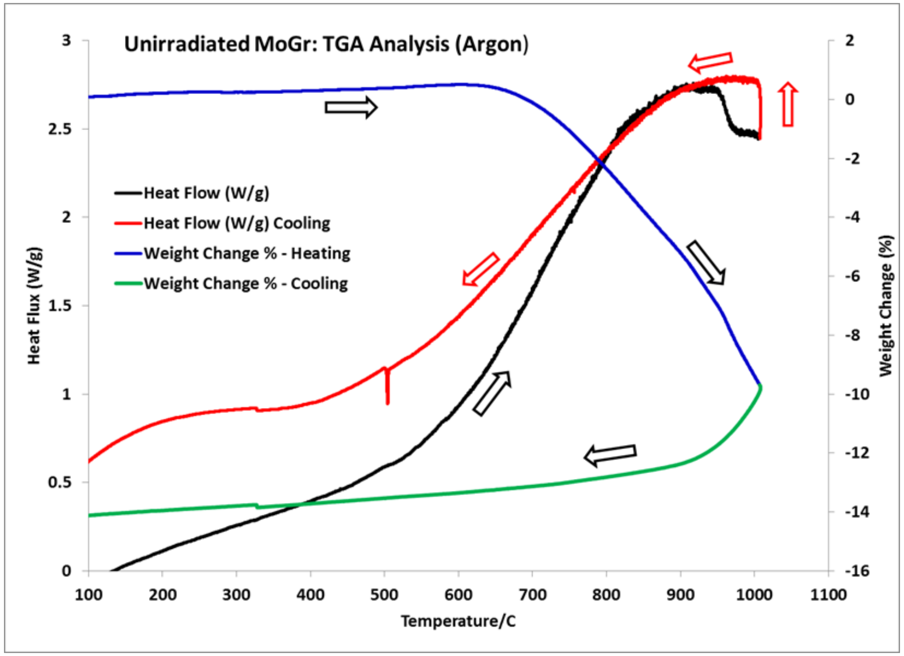


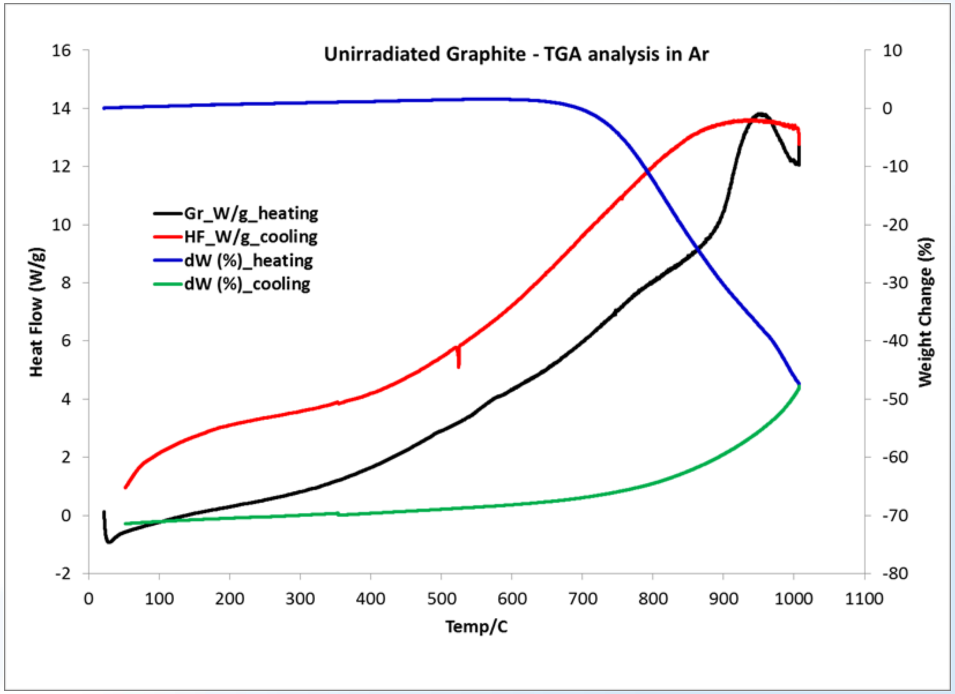


Photon Analysis and ISOTOPE Profile

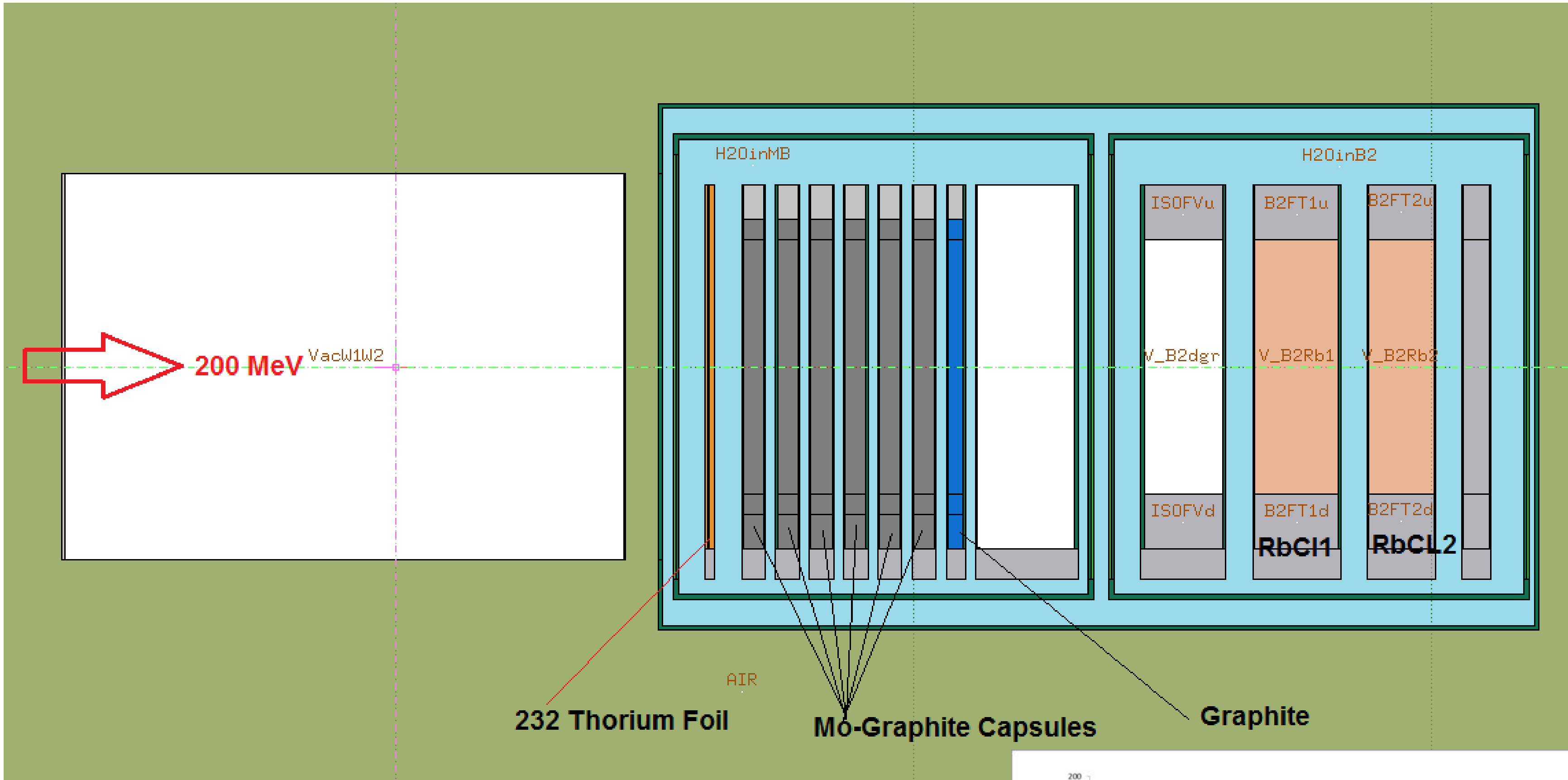


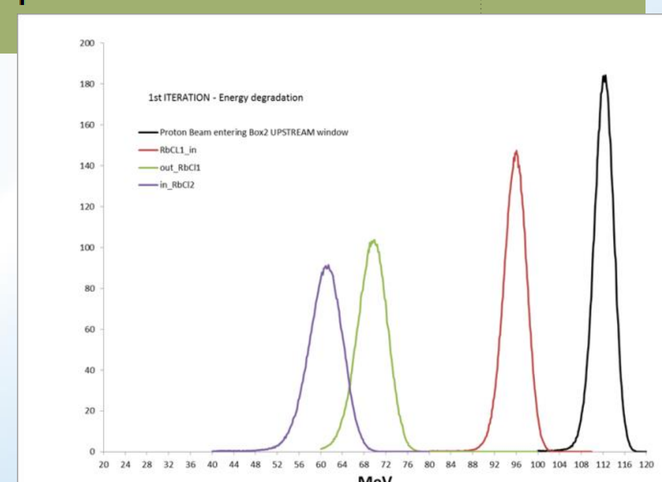
Proton Irradiation



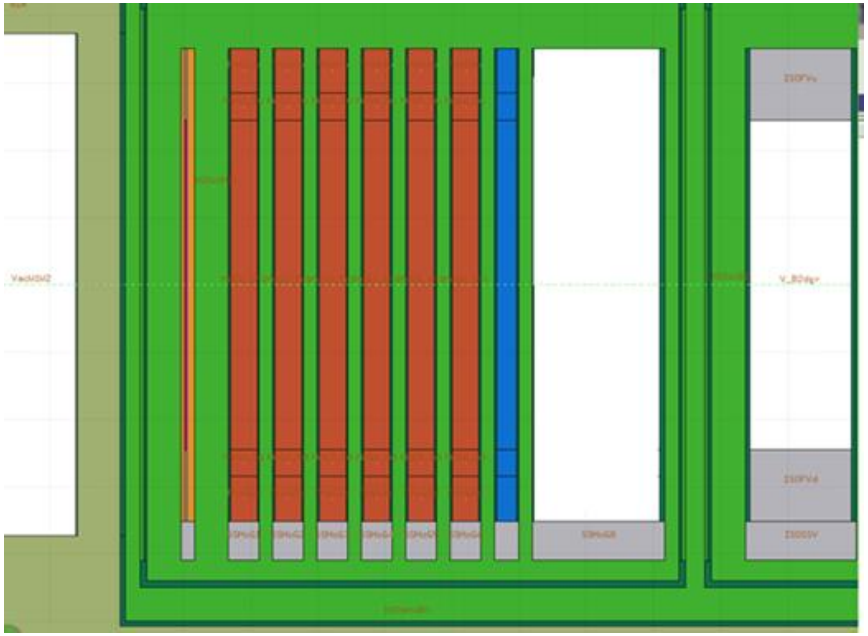


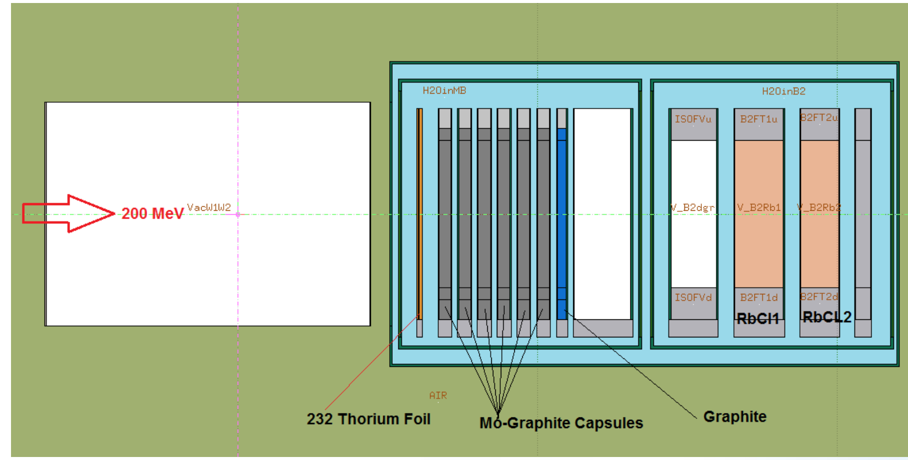
2016 RUN: 200 MeV Proton Irradiation

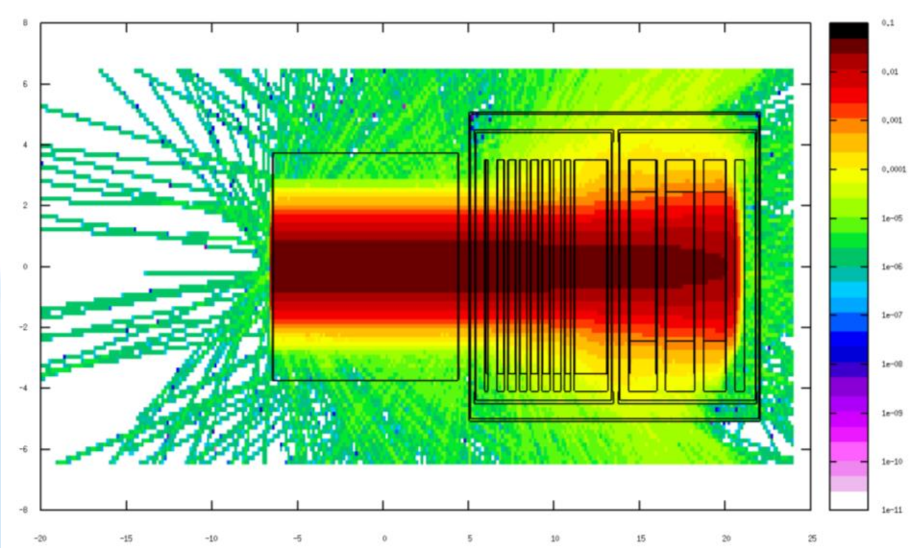


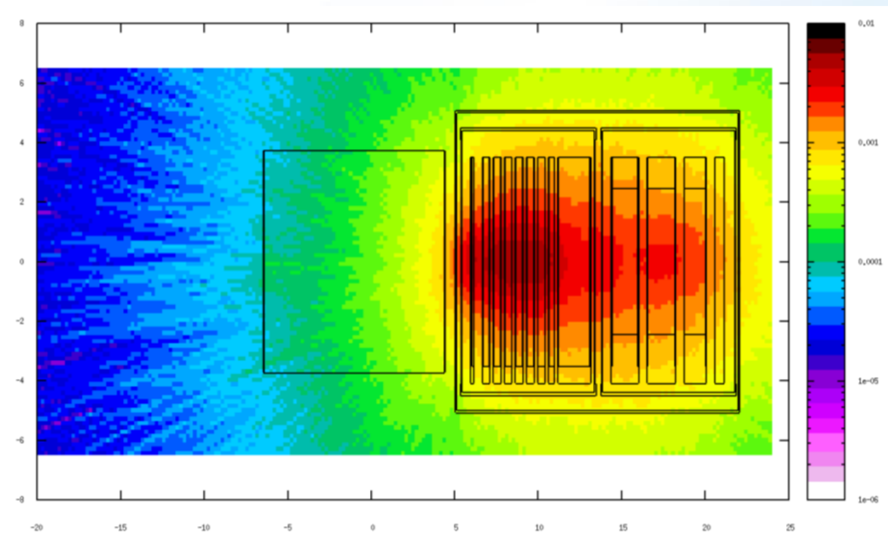


2016 RUN: 200 MeV Proton Irradiation







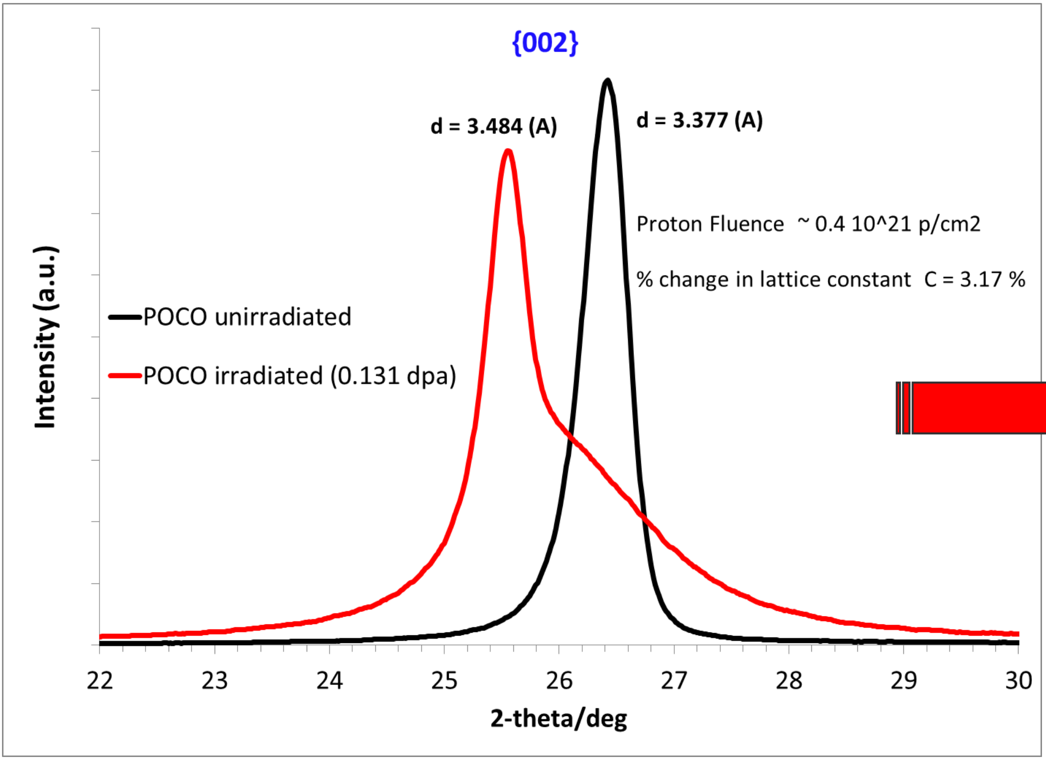


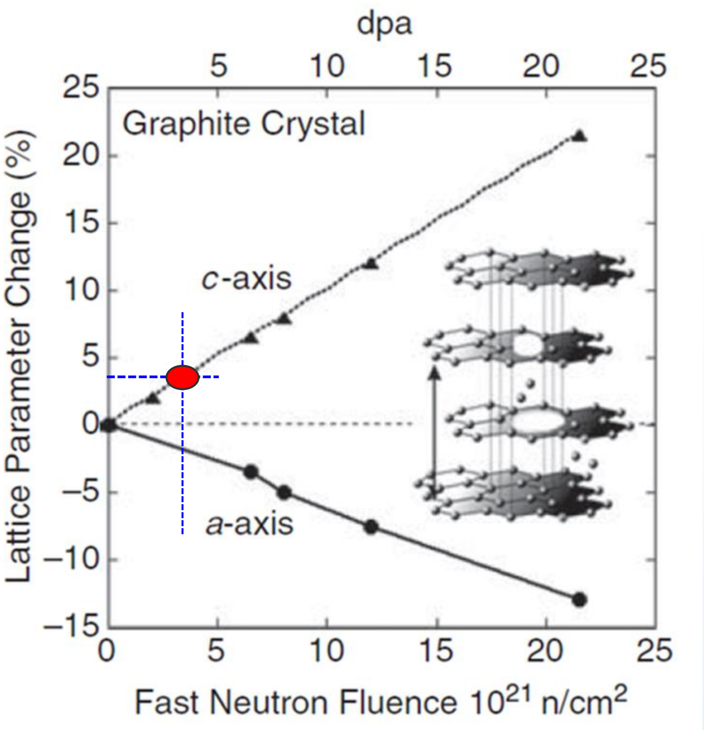
Graphite & Carbon-based Material Irradiation/Characterization

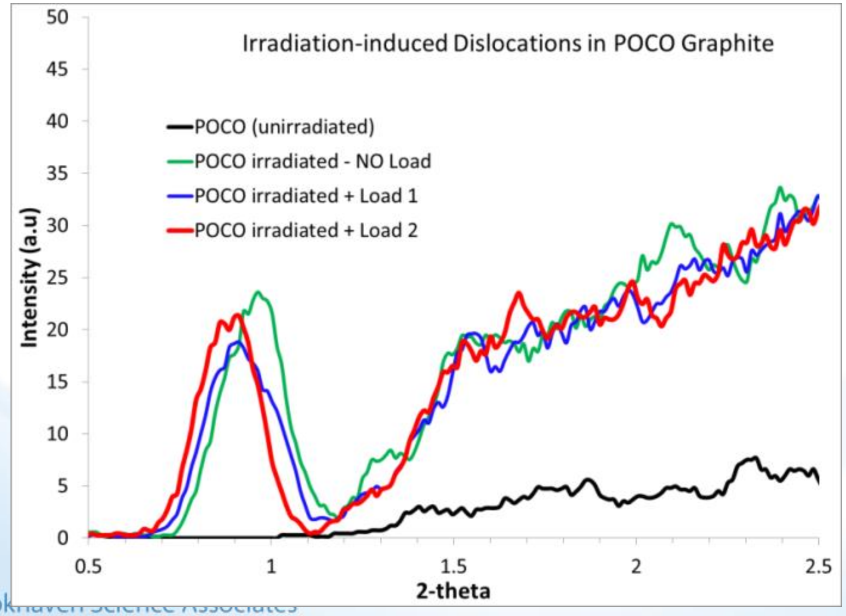
- An array of irradiation damage and post-irradiation characterization studies have been under way at BNL for graphite and carbon-based structures
- Brookhaven has a long history in the study of nuclear graphite
- BNL accelerator complex facilities (200 MeV Linac/BLIP and Tandem accelerator) provide proton, spallation fast neutron and ion irradiation beams)
- Macroscopic post-irradiation characterization utilizes the Isotope Extraction Facility (hot cells, remote handling and testing)
- Microscopic post-irradiation is performed at the BNL Synchrotron facilities (NSLS using white and monochromatic x-ray beams and now NSLS II) aided by multi-faceted characterization at the Center of Functional Nanomaterials

Graphite & Carbon-based Materials

- Reactor-grade graphite (IG-43, IG-430) under fast neutrons and protons
- Carbon fiber composites (2D C/C and 3D C/C) + SiC/SiC
- HP Target bound graphite (LBNE) – 4 grades (POCO, IG-430, Carbone and R7650)
- Newly developed structures such as Mo-GR



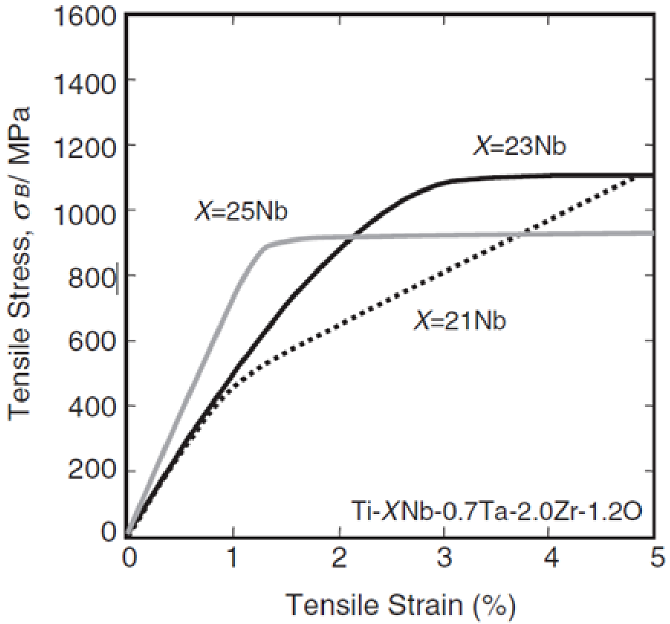


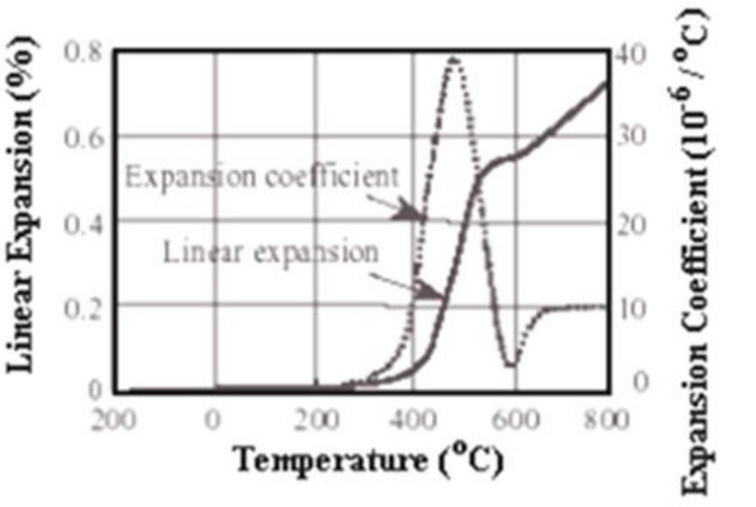


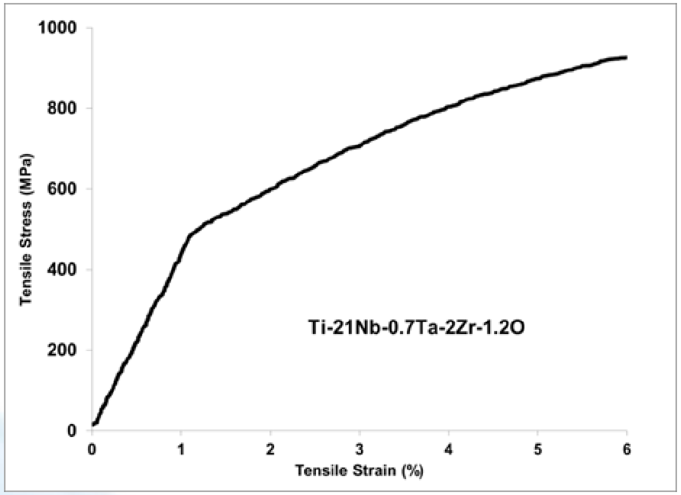
BNL EDXRD study on irradiated graphite revealed the following important correlation:
Damage expressed in terms of MEASURABLE quantities (i.e. crystal lattice changes) is achieved much faster and at much lower FLUENCE or DPA by energetic protons than fast neutrons.
BNL finding is set to a factor of ~10

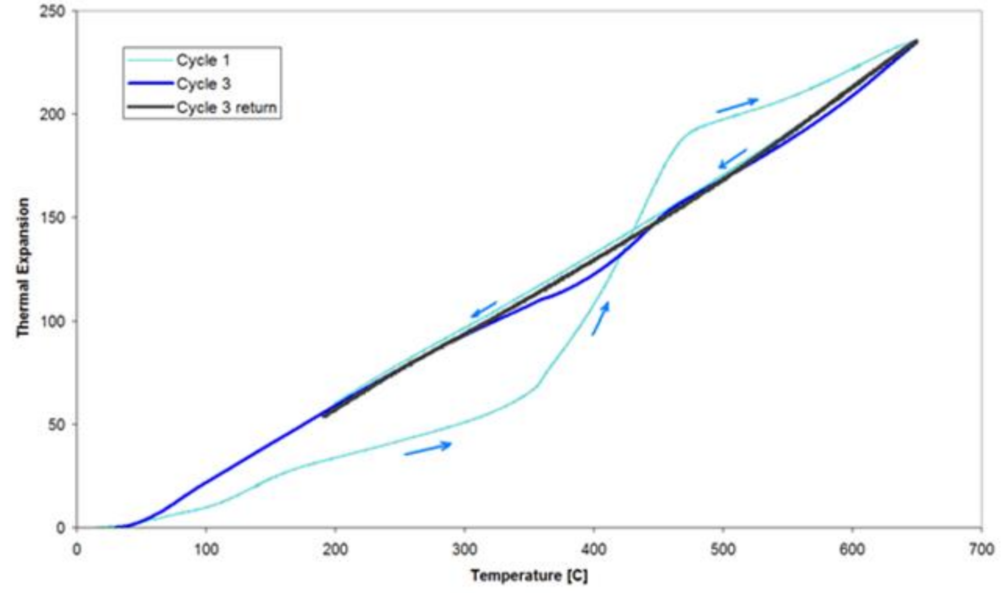
Titanium Alloy Irradiation/Characterization Studies at BNL

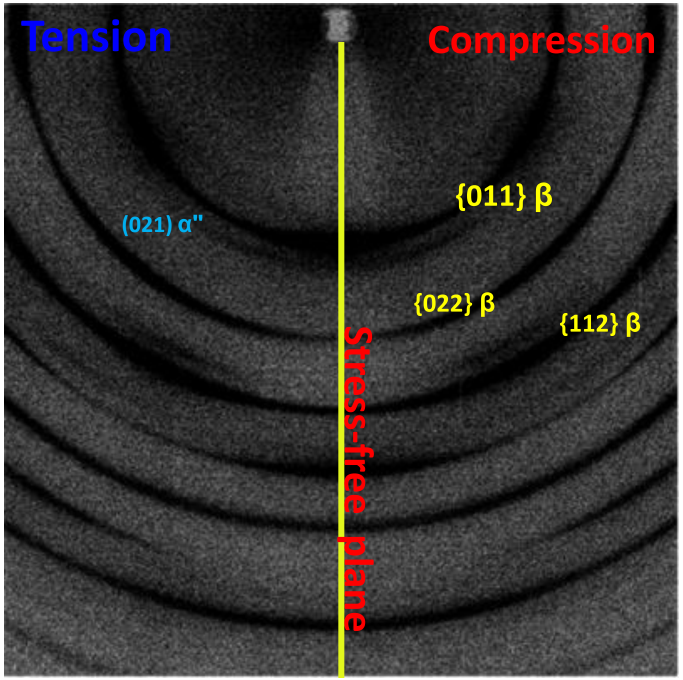
- An array of irradiation damage and post-irradiation characterization studies have been under way at BNL for Ti-alloys that include
  - (α + β) Ti-6Al-4V alloy
  - β-titanium alloy Gum metal (Ti-21Nb-0.7Ta-2.Zr-1.2O)
- Both alloys were investigated as candidates for HP targets in the Neutrino Factory initiative
- The (α + β) Ti-6Al-4V has also been studied as a substrate of ceramic nano-structured coatings for potentially nuclear applications (fast neutron and elevated temperatures)
- 200 MeV protons and spallation generated fast neutrons at the BNL complex were used for irradiation induced damage
- Macroscopic post-irradiation and EDXRD/XRD studies at the BNL synchrotrons were employed to study microstructural changes and damage

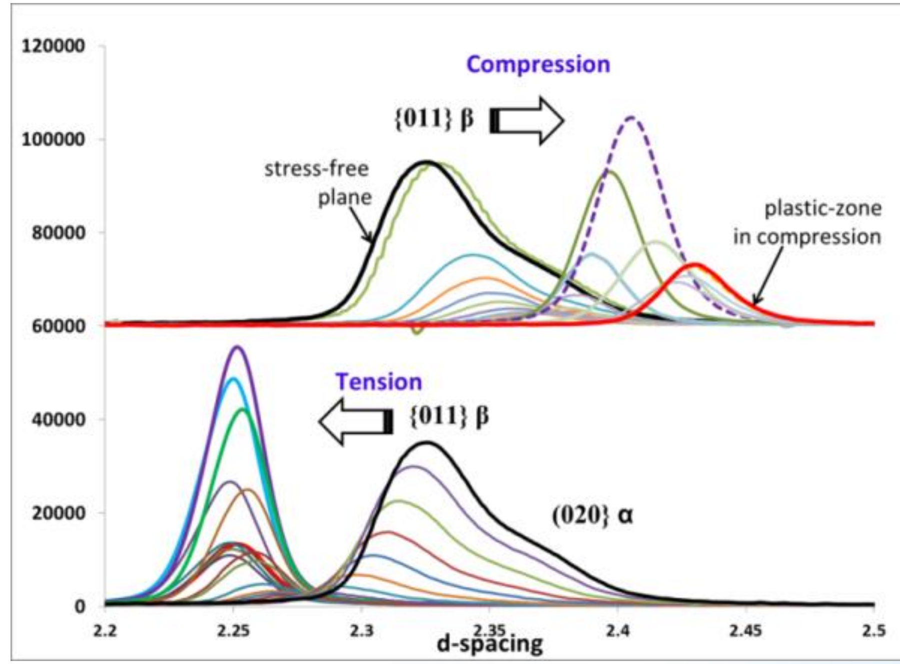

Tensile Stress, σ_B/ MPa
X=23Nb
X=25Nb
X=21Nb
Ti-XNb-0.7Ta-2.0Zr-1.2O
Tensile Strain (%)

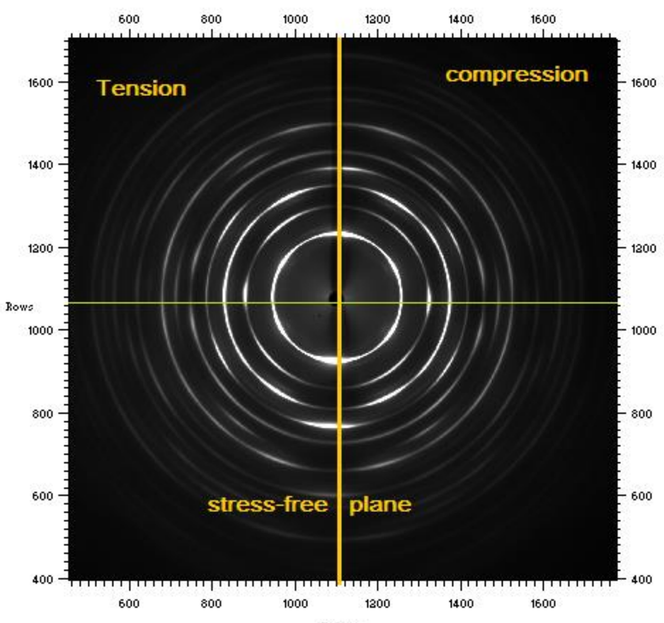

Linear Expansion (%)
Expansion coefficient
Linear expansion
Temperature (°C)
Expansion Coefficient (10^{-6} / °C)

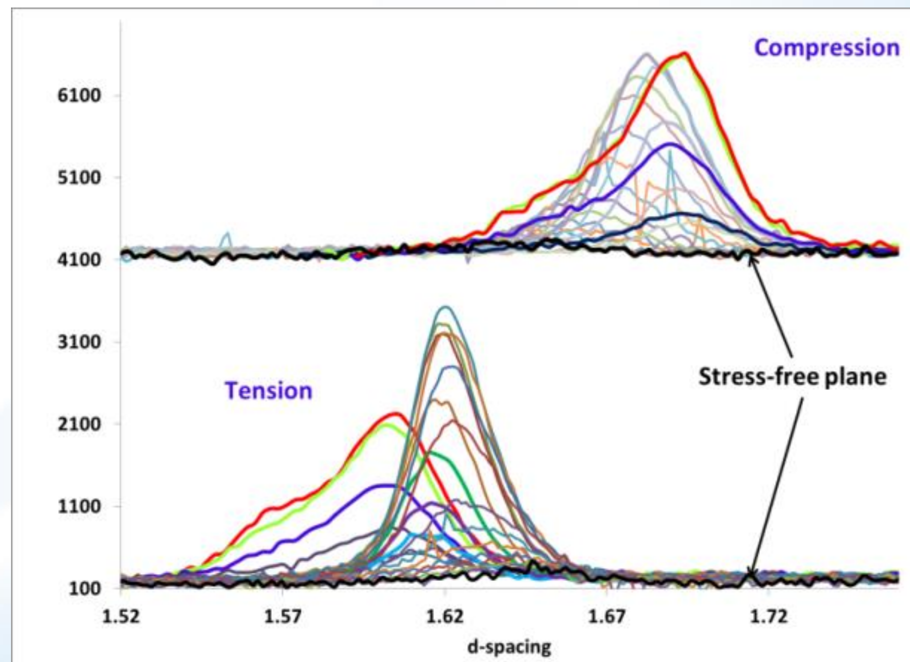

Tensile Stress (MPa)
Ti-21Nb-0.7Ta-2Zr-1.2O
Tensile Strain (%)


Cycle 1
Cycle 3
Cycle 3 return
Thermal Expansion
Temperature [C]

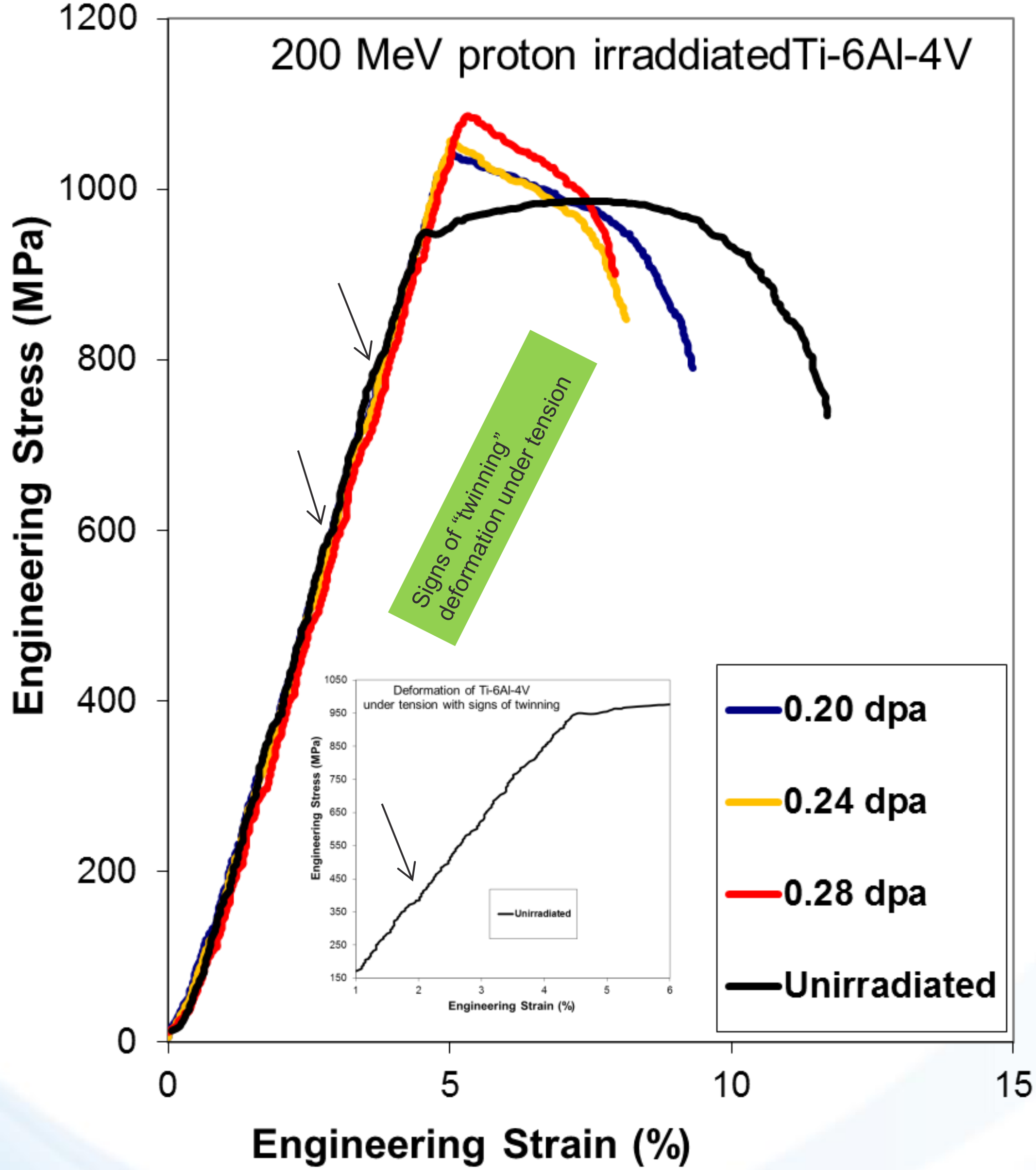

Tension
Compression
{011} β
(021) α"
{022} β
{112} β
Stress-free plane

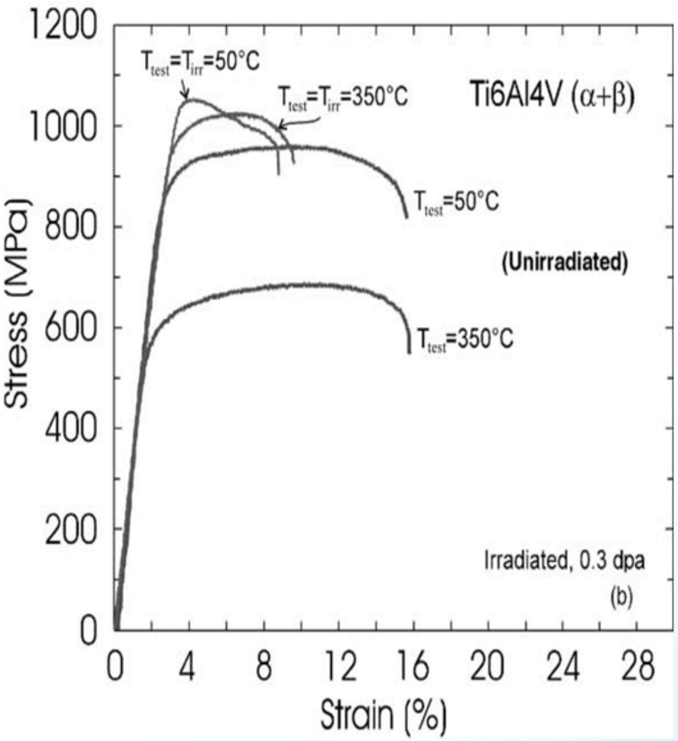

Compression
{011} β
stress-free plane
plastic-zone in compression
Tension
{011} β
(020) α
d-spacing


Tension
compression
stress-free plane
Rows
Columns


Compression
Tension
Stress-free plane
d-spacing

Bro
Sim





Tensile and fracture toughness properties of unirradiated and neutron irradiated titanium alloys
S. T€ahtinen a,*, P. Moilanen a, B.N. Singh b, D.J. Edwards c

Journal of Nuclear Materials 307–311 (2002) 416–420

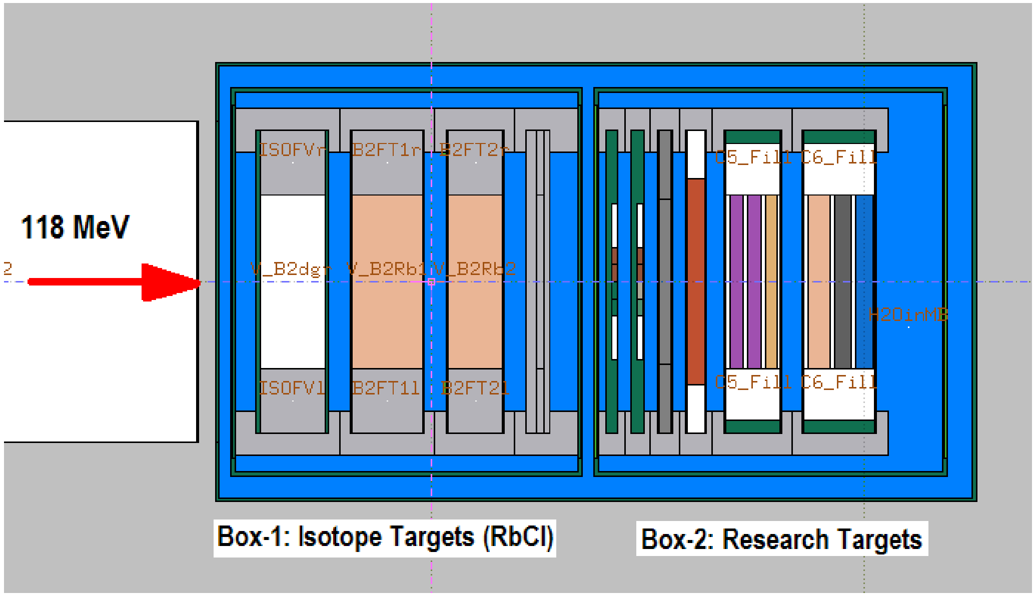
Spallation Neutron Irradiation

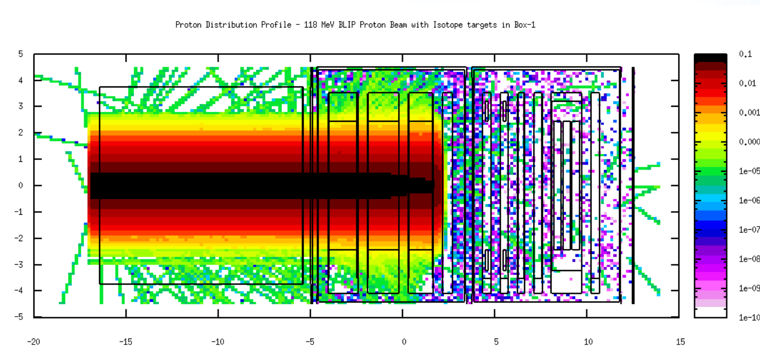
Irradiation damage studies from mixed spectrum (dominated by fast neutrons)

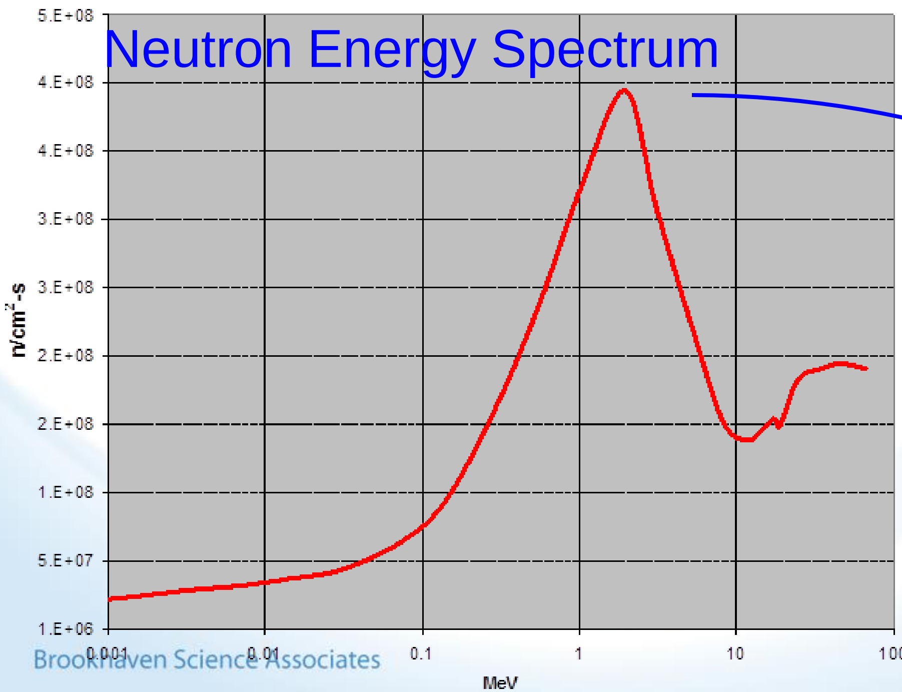
Studies:

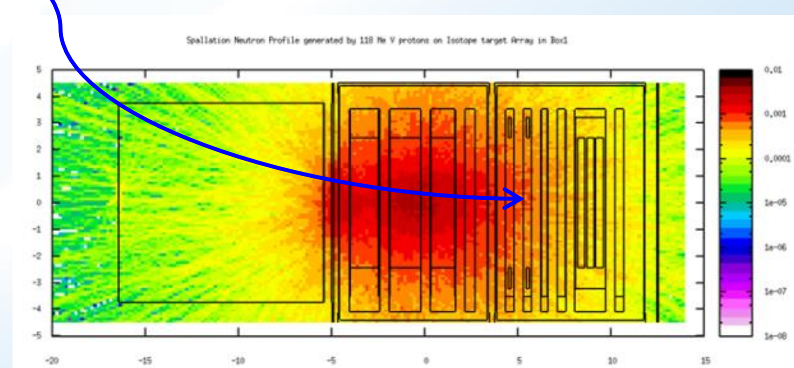
- Fusion Reactor Materials and Composites
- DOE-NE materials (super-alloys, ceramic and amorphous coatings on reactor steels, etc.)

Spallation-induced Fast Neutron Irradiation at BLIP

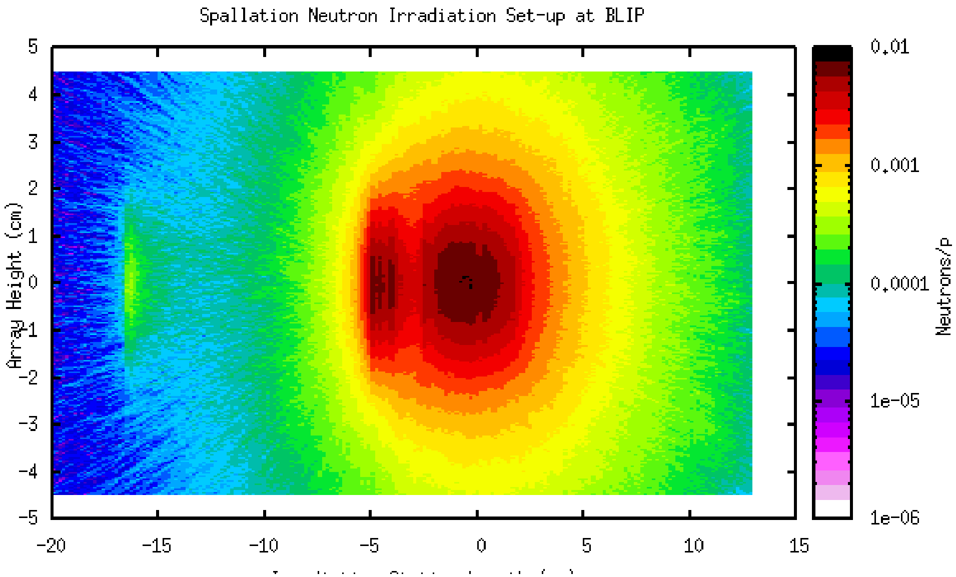


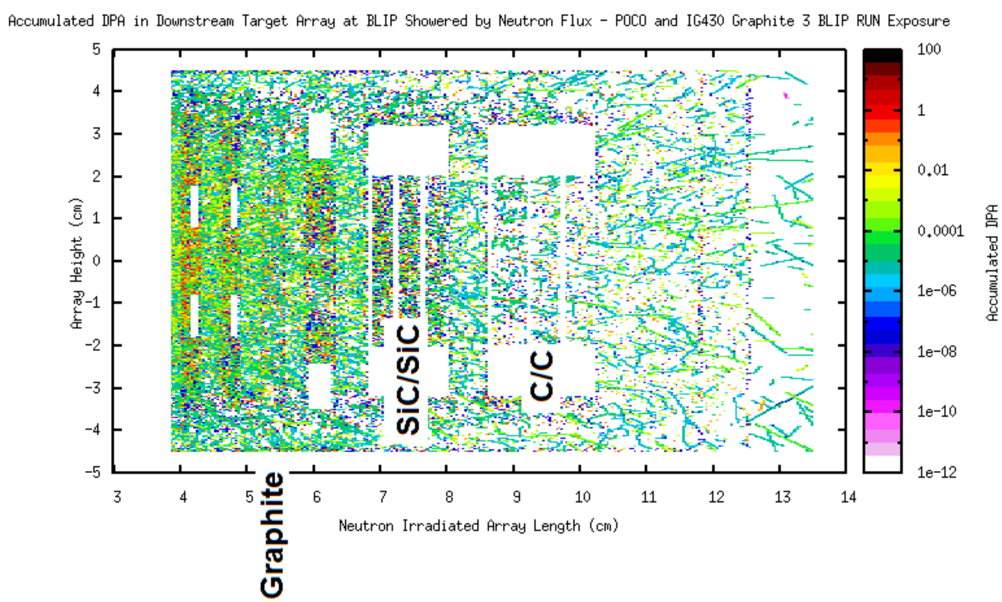




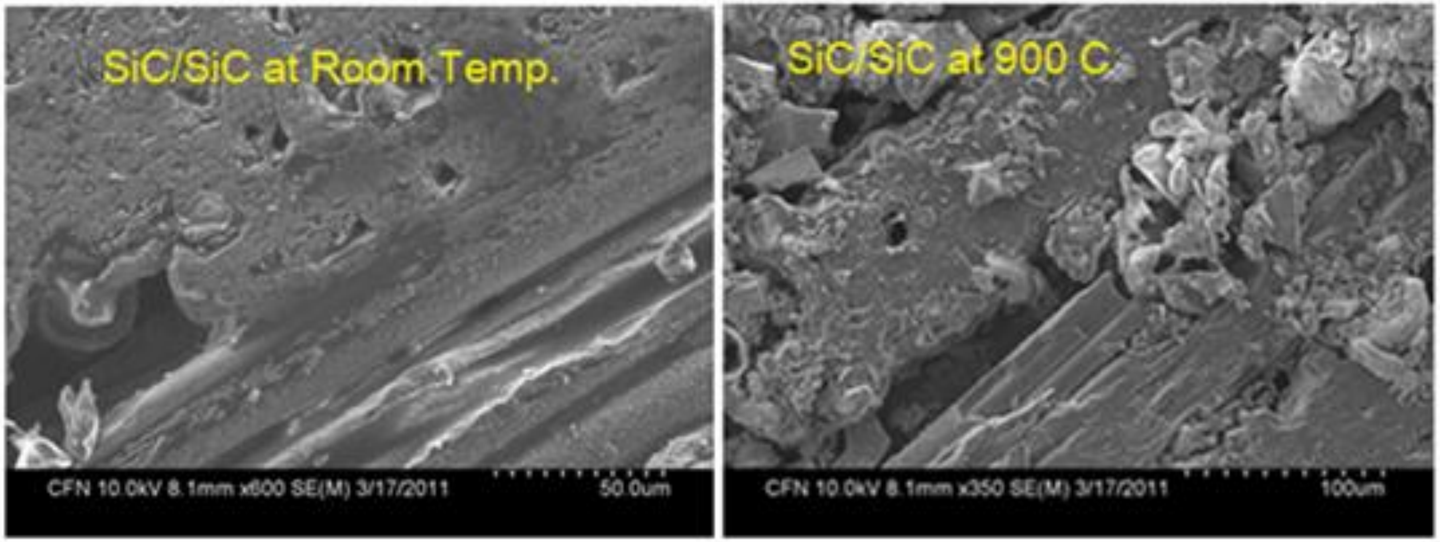


Spallation-induced Fast Neutron Irradiation at BLIP



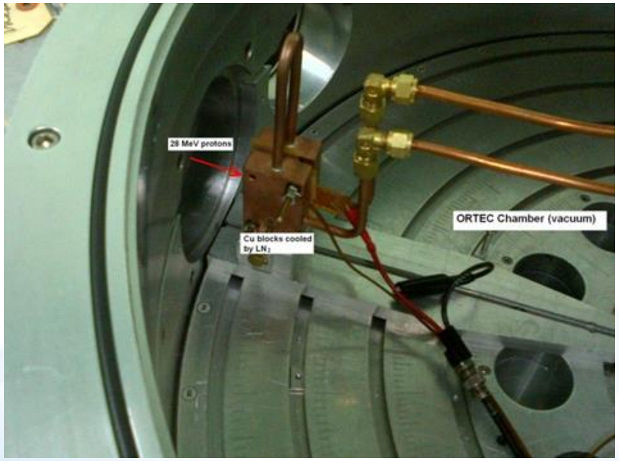


SiC/SiC Irradiation



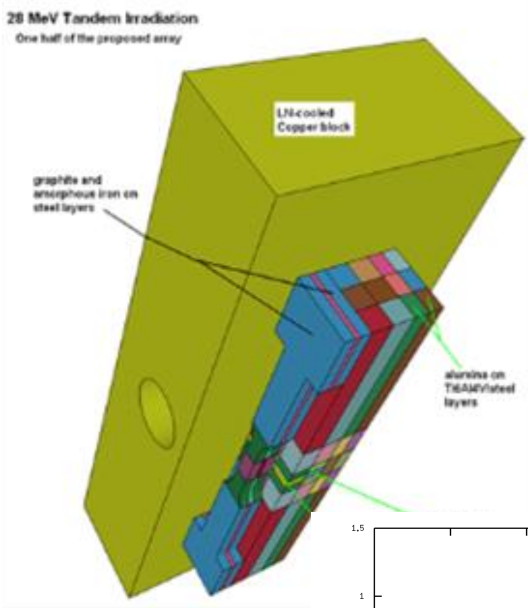
28 MeV Proton & Heavy ion irradiation at Tandem

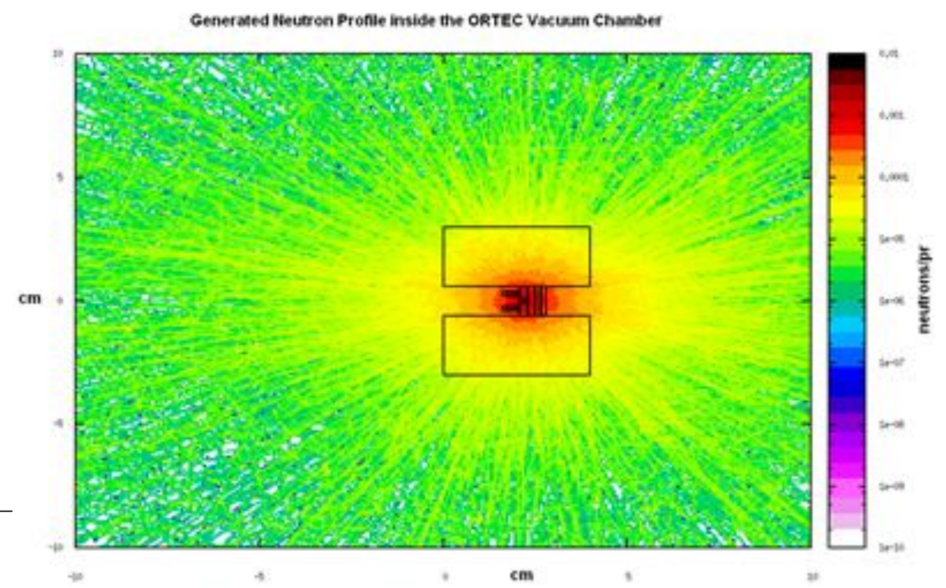
Target Irradiation Beamline

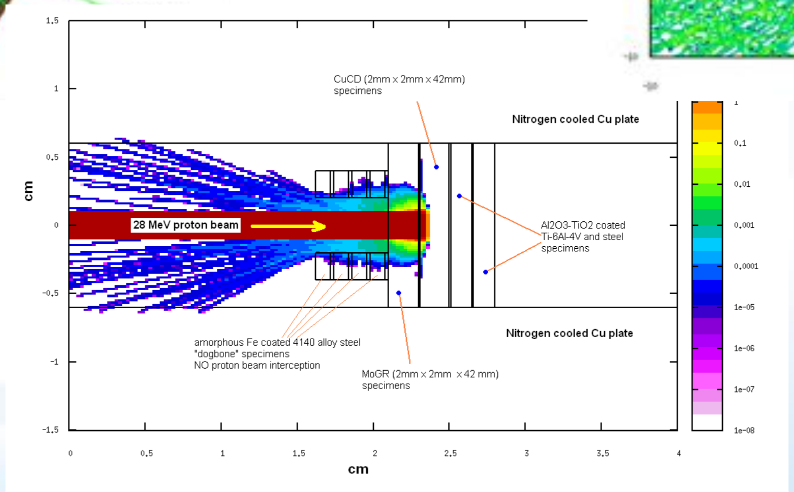


28 MeV Proton & Heavy ion irradiation at Tandem

Recent 28 MeV proton + spallation neutron irradiation experiment at sub-zero temperatures at Tandem (Simos, et al)

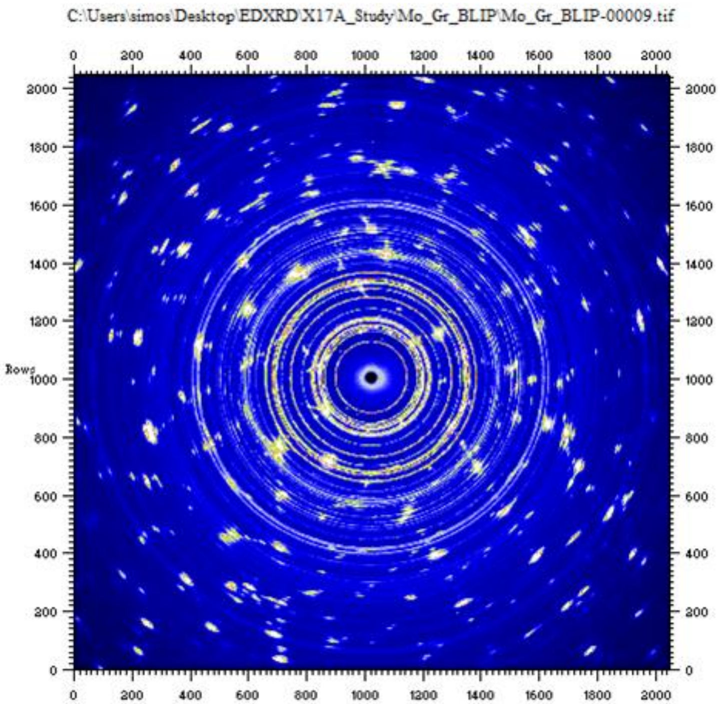


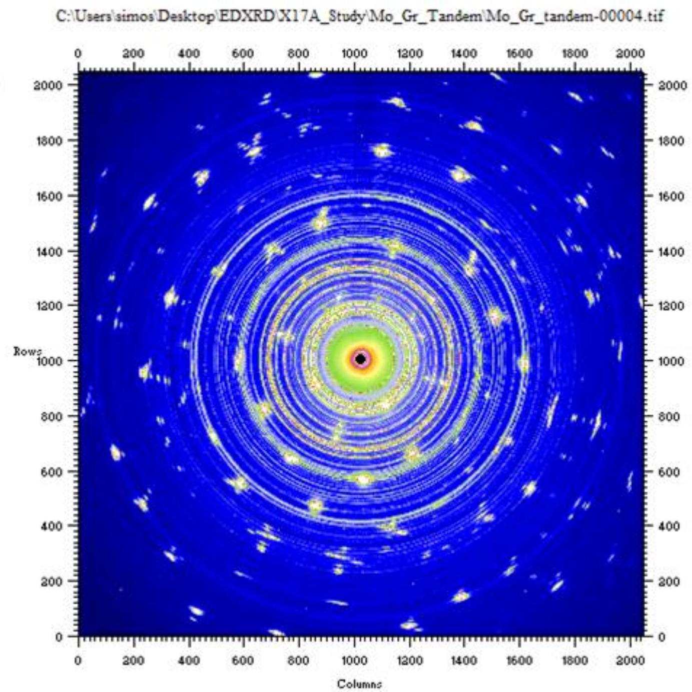


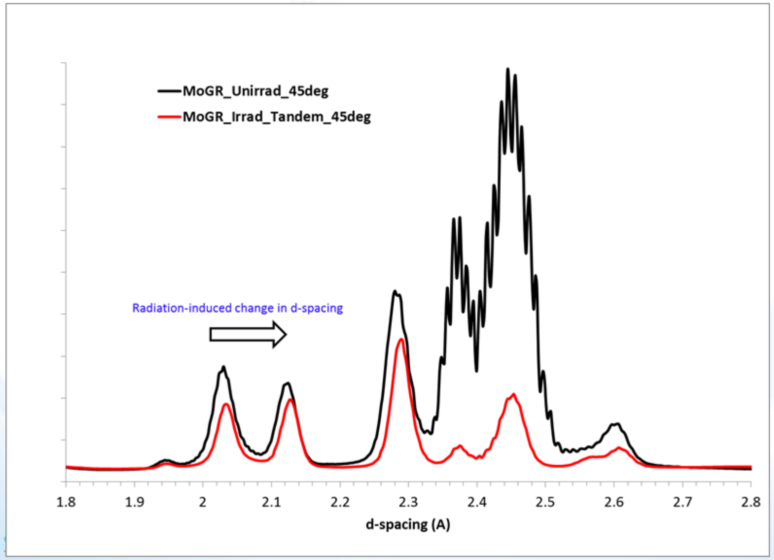


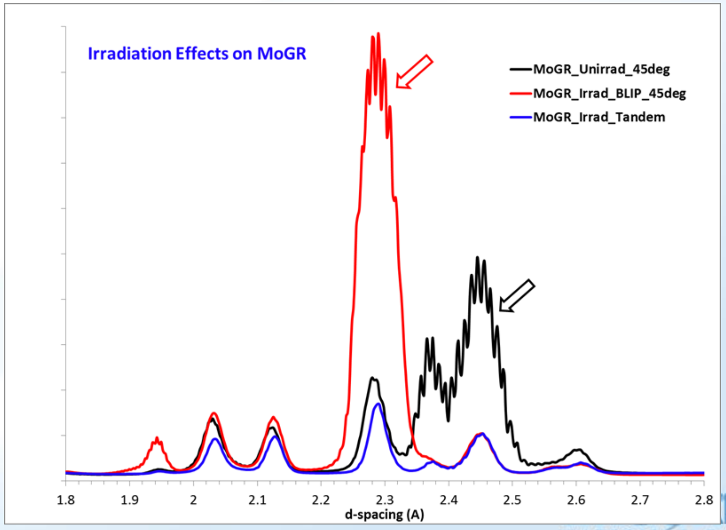
BROOKHAVEN NATIONAL LABORATORY

Irradiation at sub-zero Temp & X-ray Diffraction

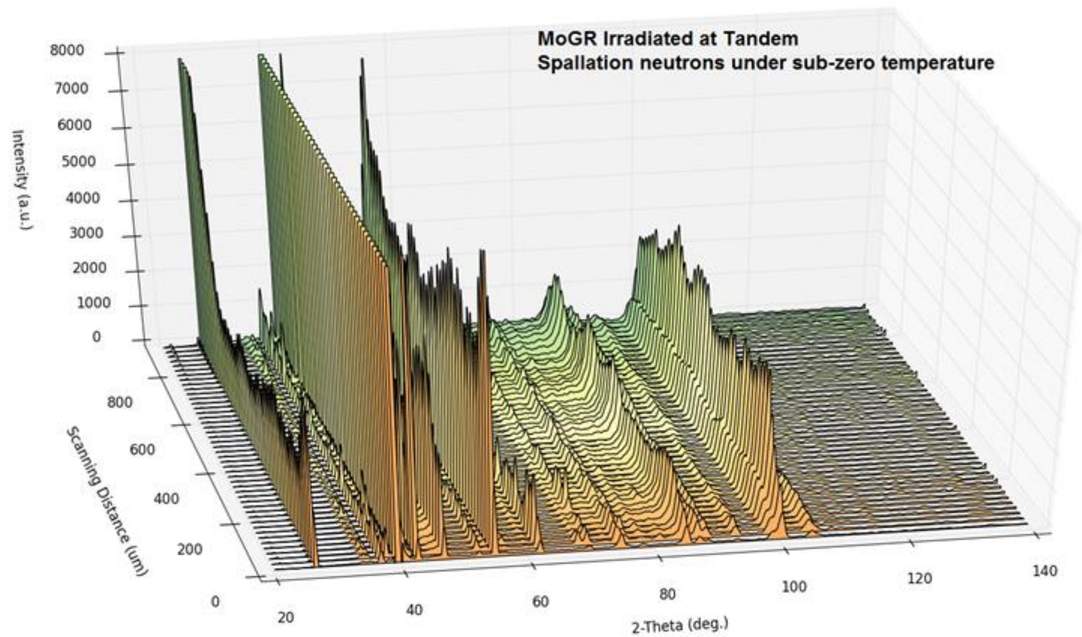


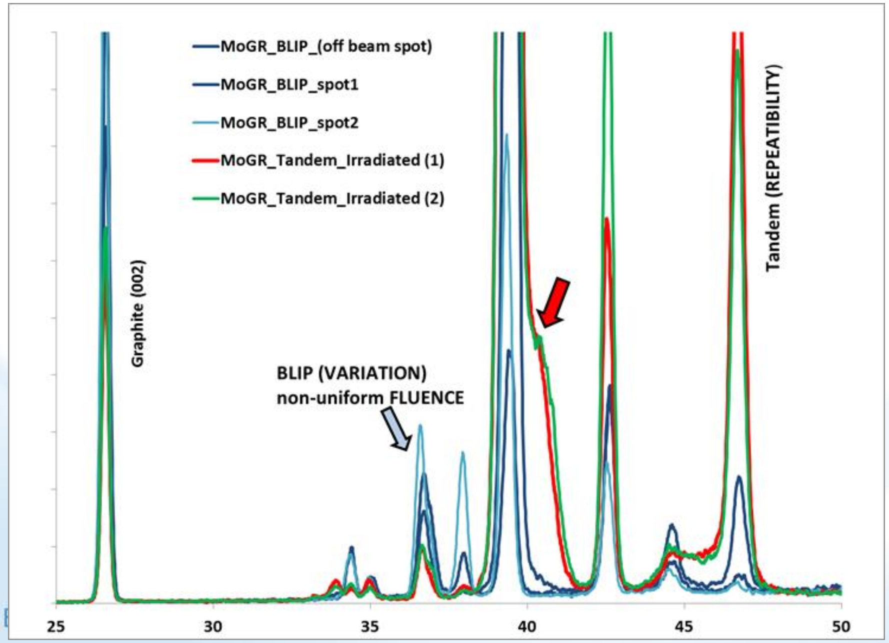


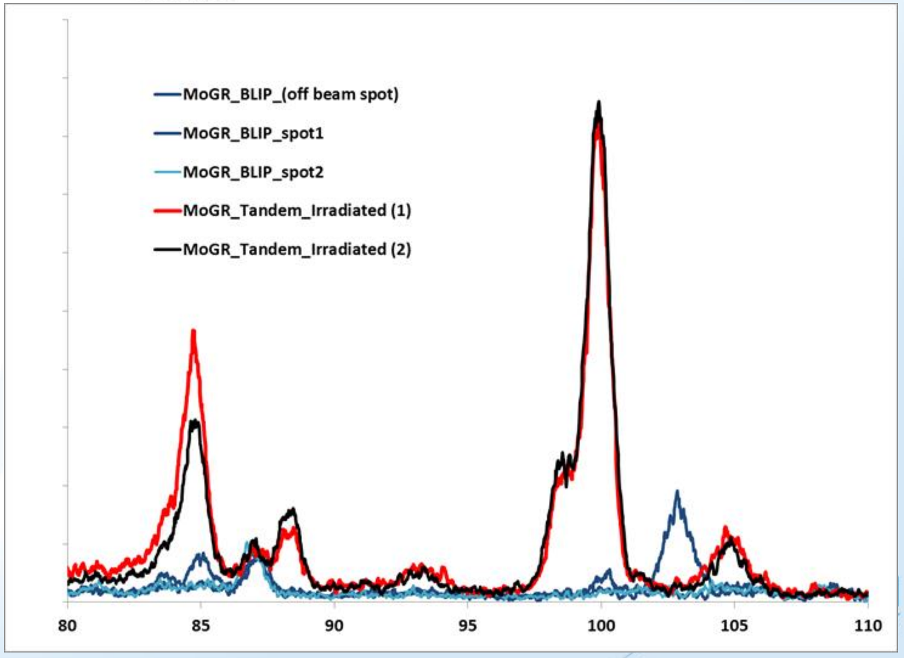




Irradiation at sub-zero Temp & X-ray Diffraction

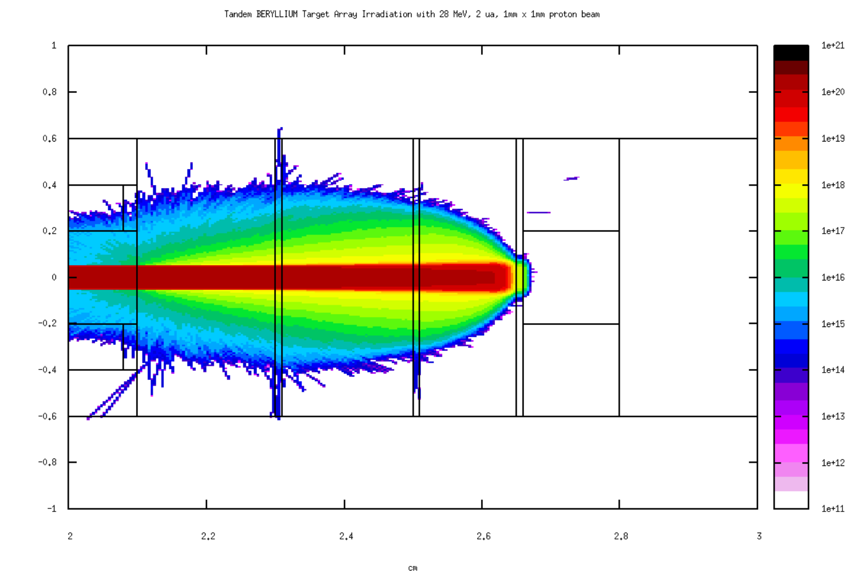


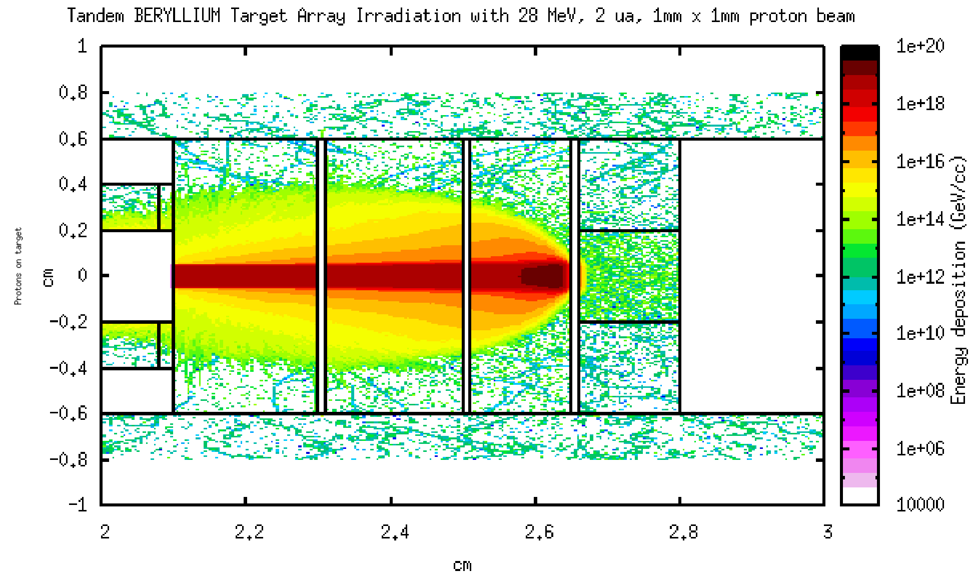


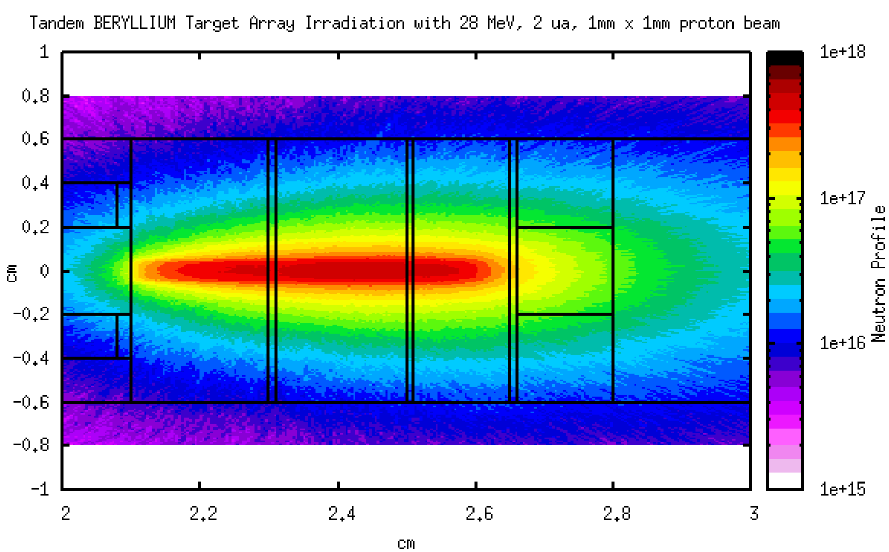


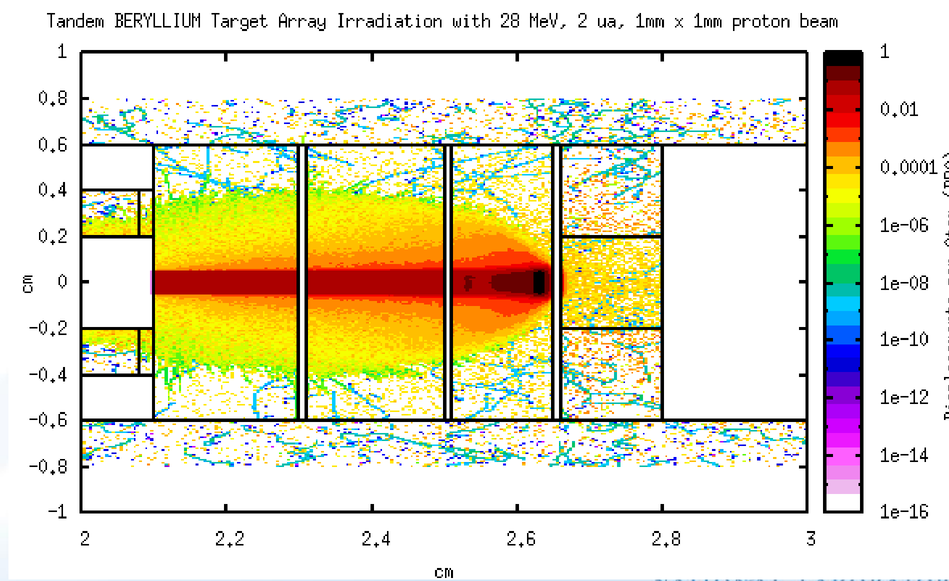
What Damage Can One Achieve at Tandem?

28 MeV protons on BERYLLIUM target array

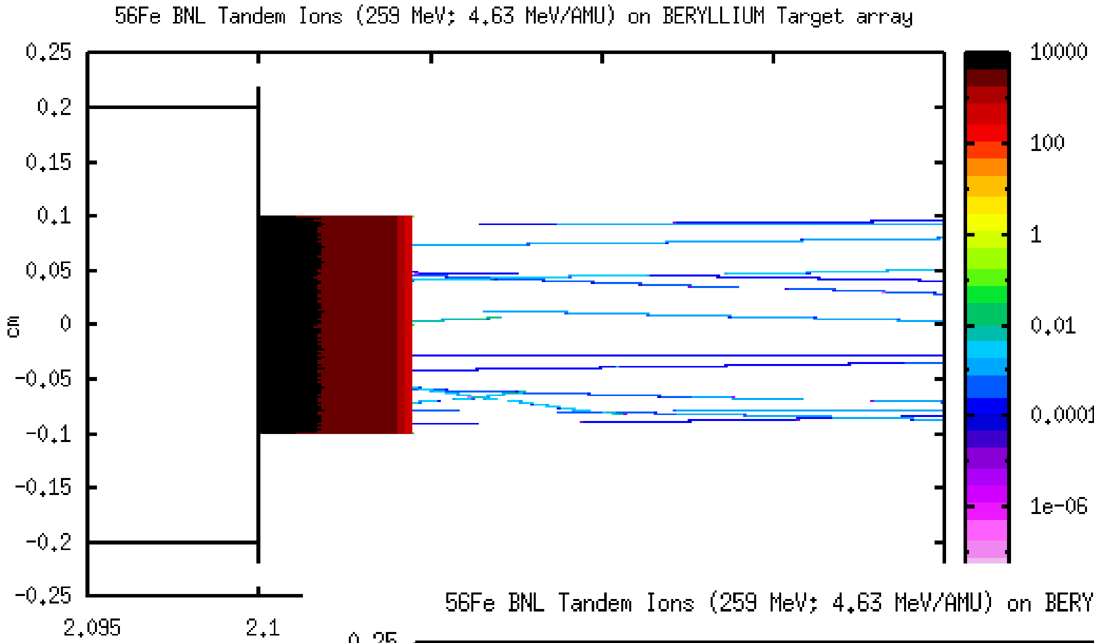


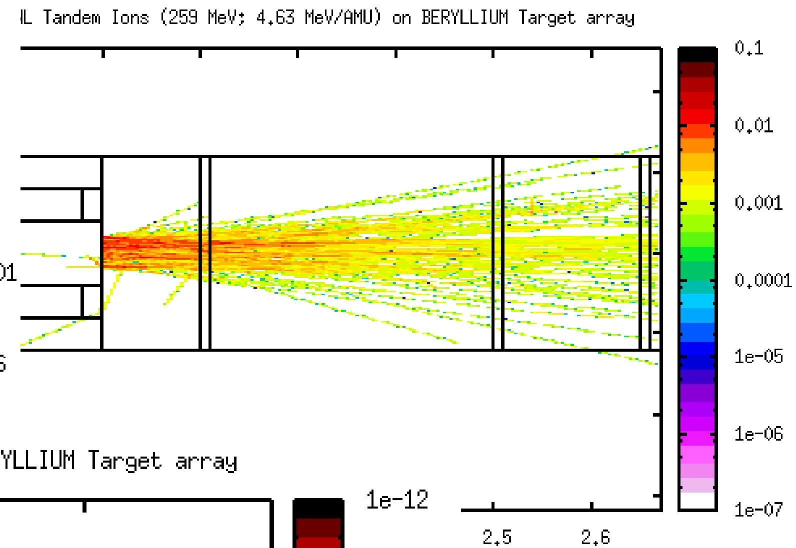


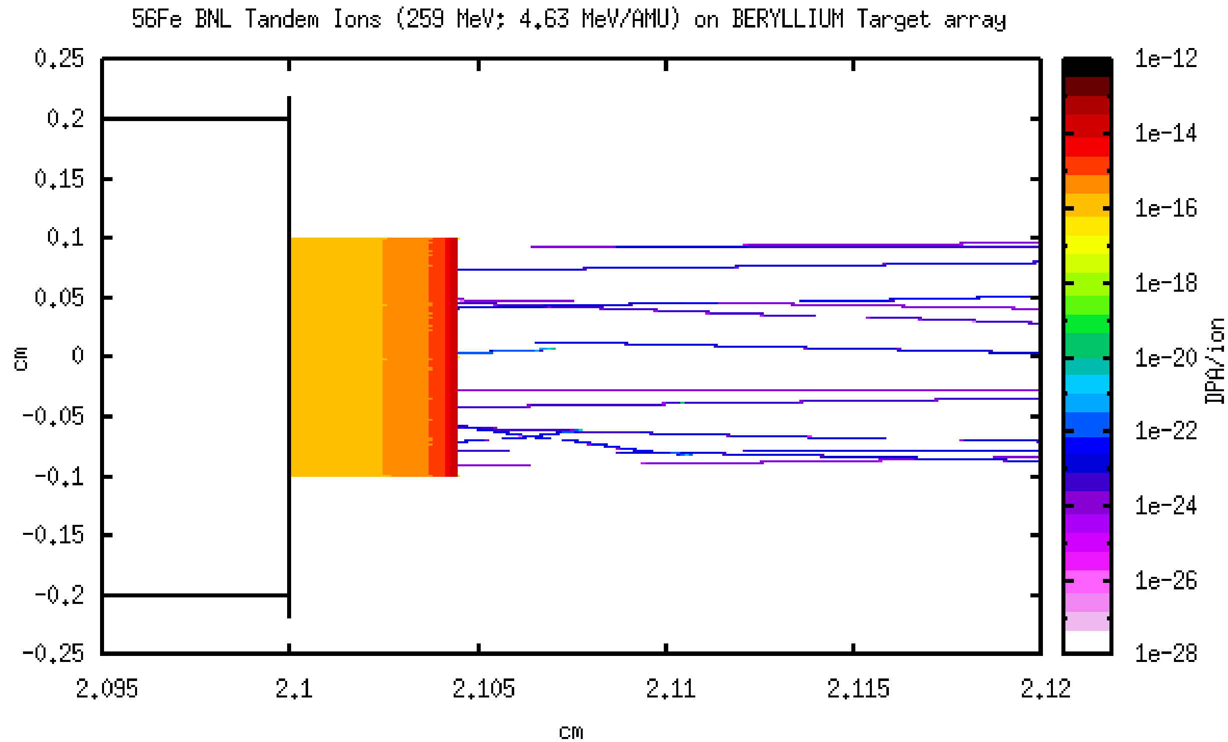




^{56}Fe ion on Be target Array







BNL Post-Irradiation Facilities

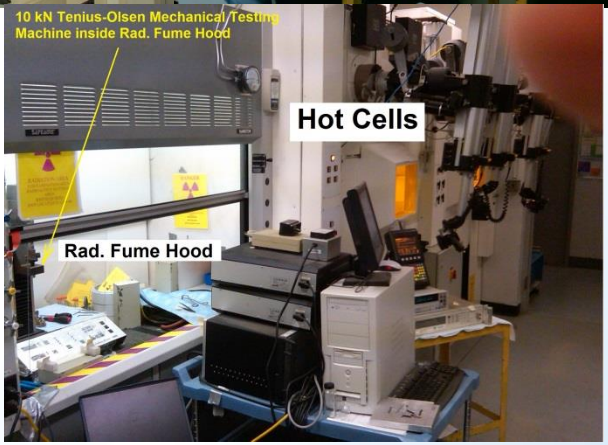
Isotope Extraction and Processing Facility at BNL

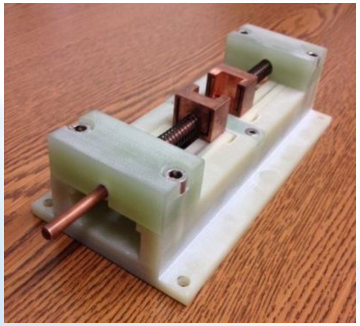
Experimental Facility occupies 2 hot cells and a HEPA-filtered fume hood

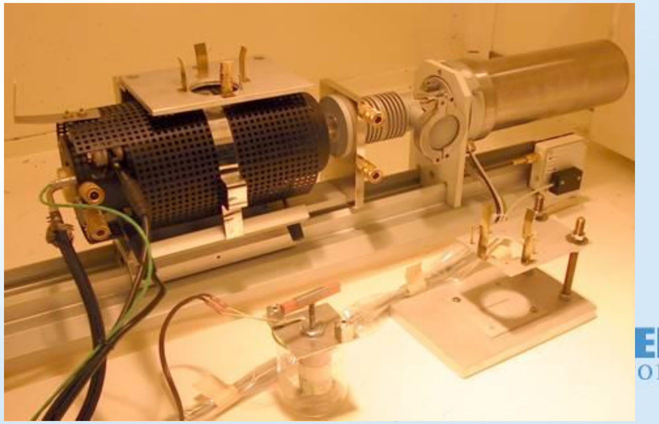
PIE analyses performed are:

Stress-strain (tension, 3-point and 4-point bending)
Thermal Expansion and annealing (extremely sensitive dilatometer)
Thermal Conductivity (electrical resistivity)
Magnetic Whole probe
Ultrasonic measurements

PLUS
Photon spectra and isotopic analysis
Activity measurements
Weight loss or gain







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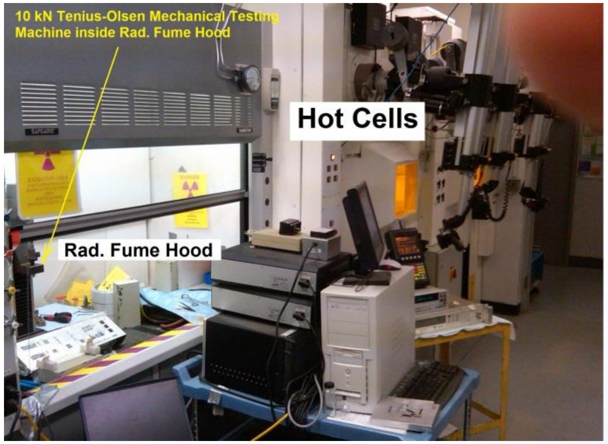
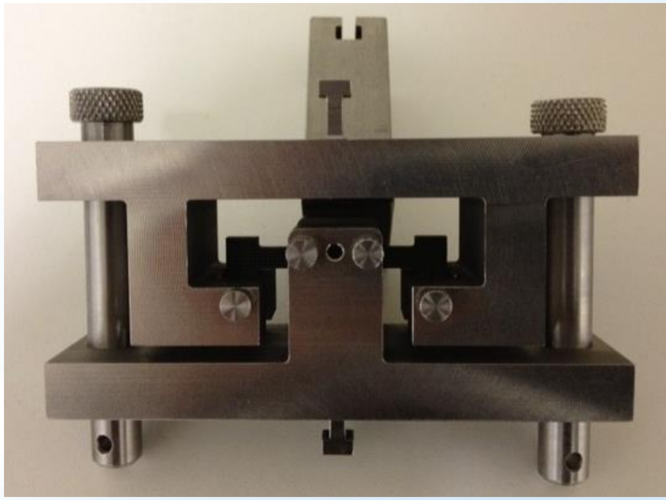
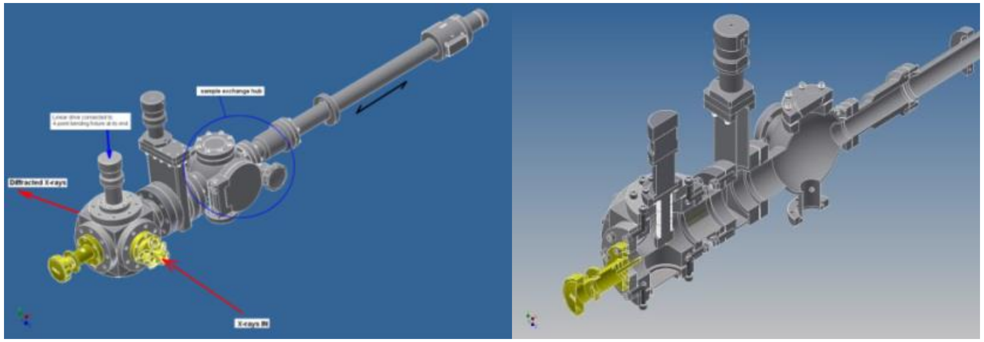


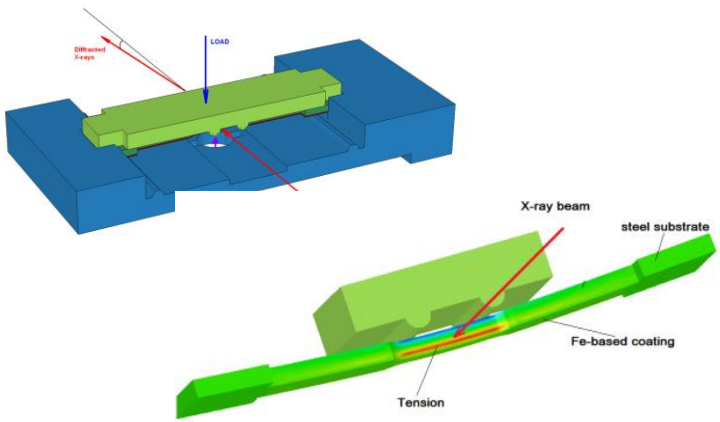


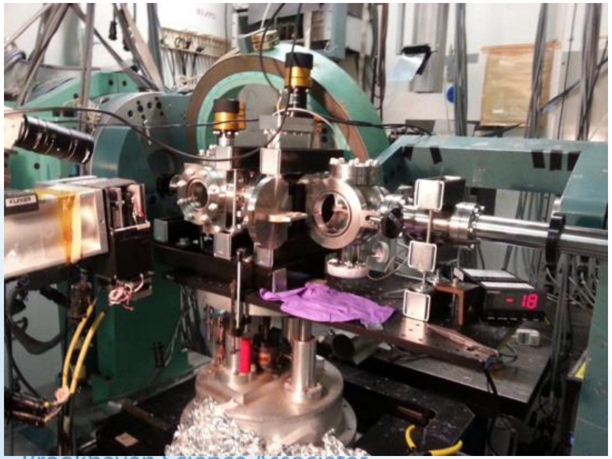
BNL Post-Irradiation Facilities X-ray Diffraction at NSLS II

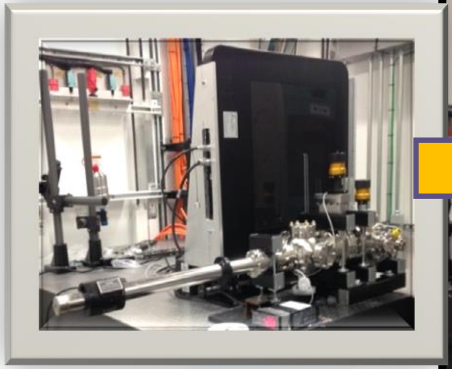


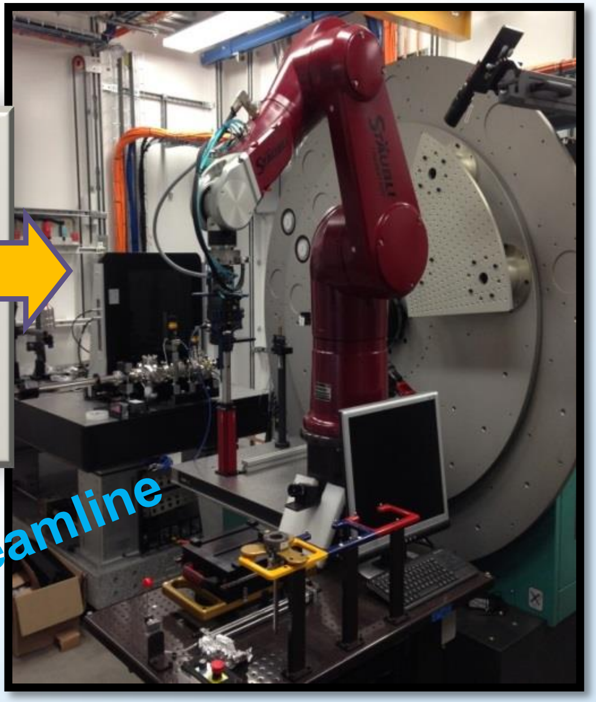
X-ray diffraction studies of irradiated samples with the aid of a multi-functional experimental stage enabling:

- Laser-induced annealing
- Tension/twisting/4-point-bending
- Exposure to different environments
- Diamond anvil cell to be introduced in future update



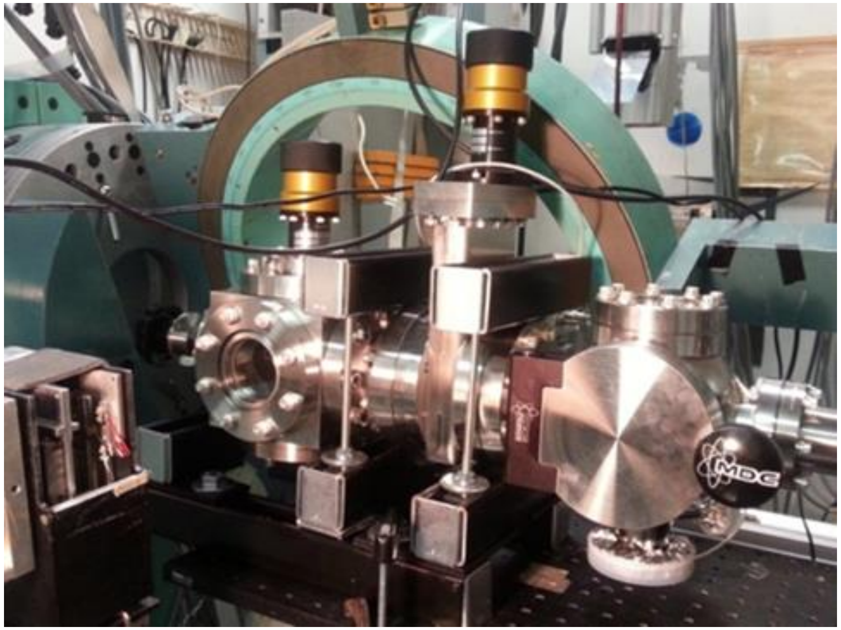


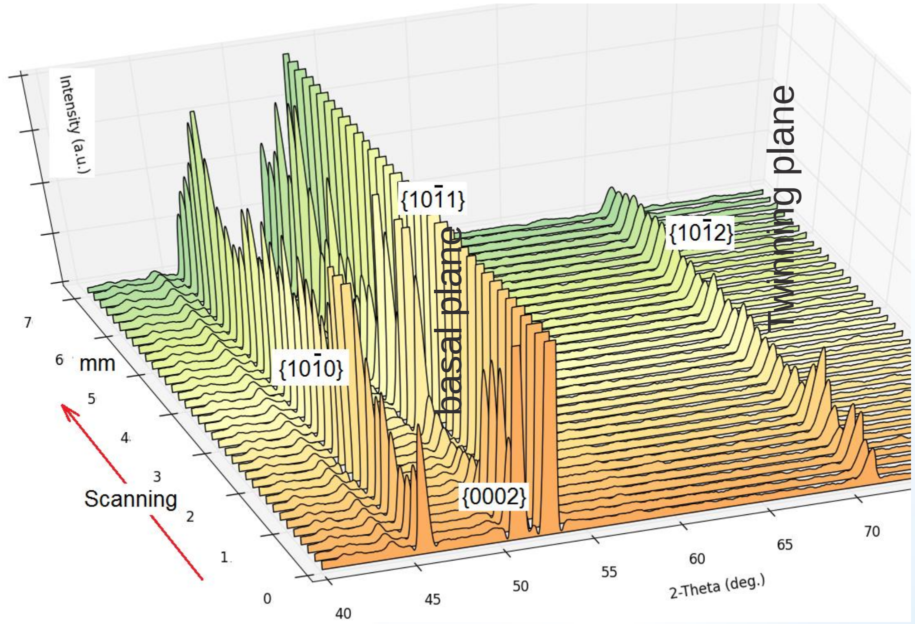


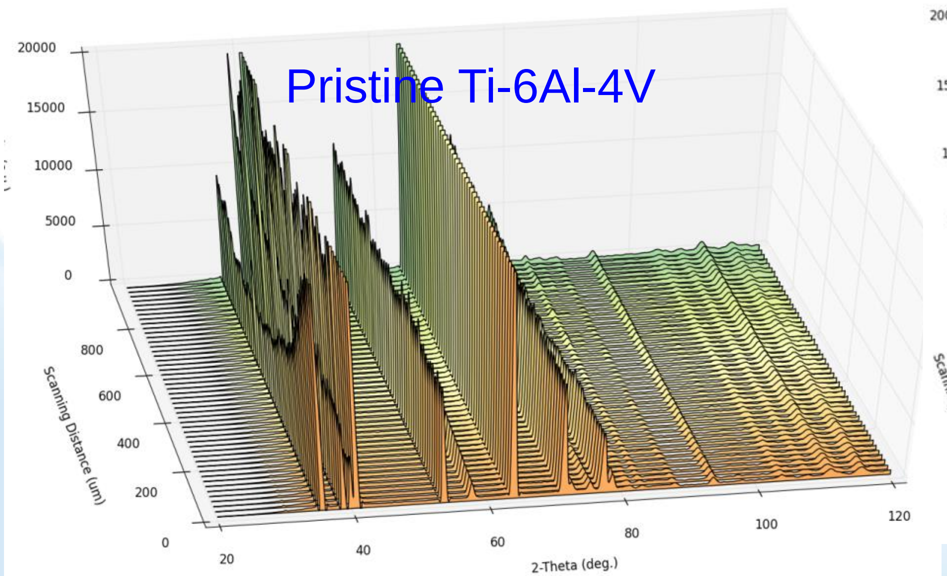


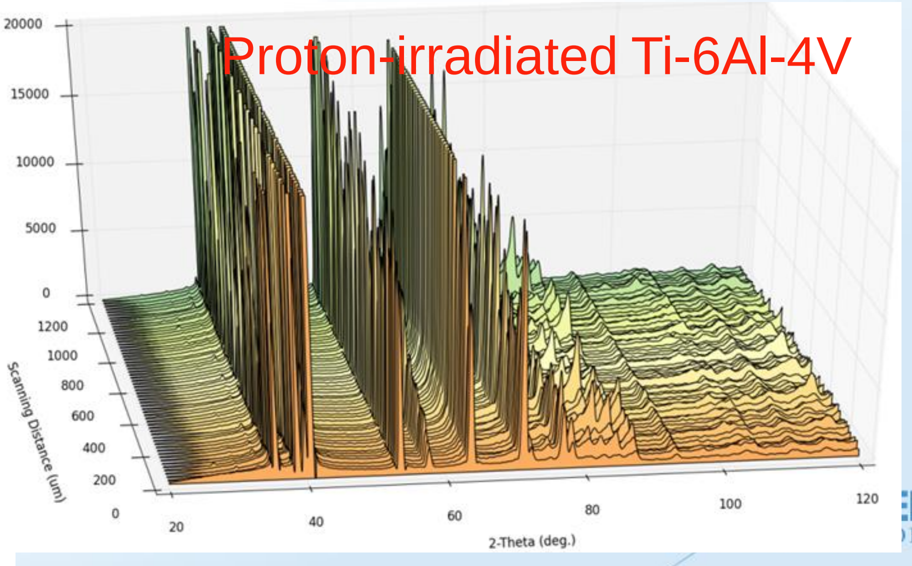
Stage at NSLS II XPD Beamline

BNL Post-Irradiation Facilities X-ray Diffraction at then NSLS



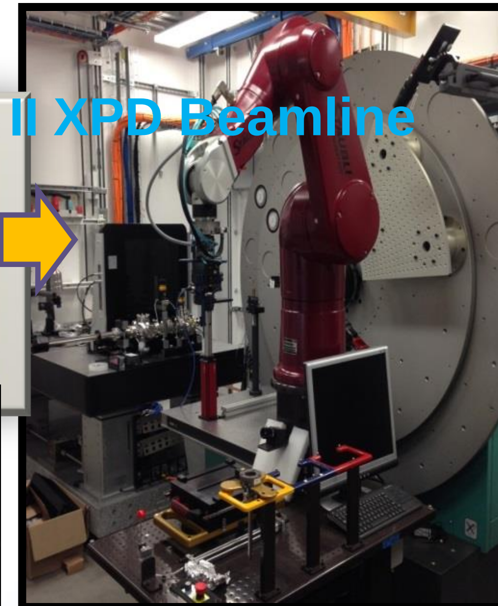


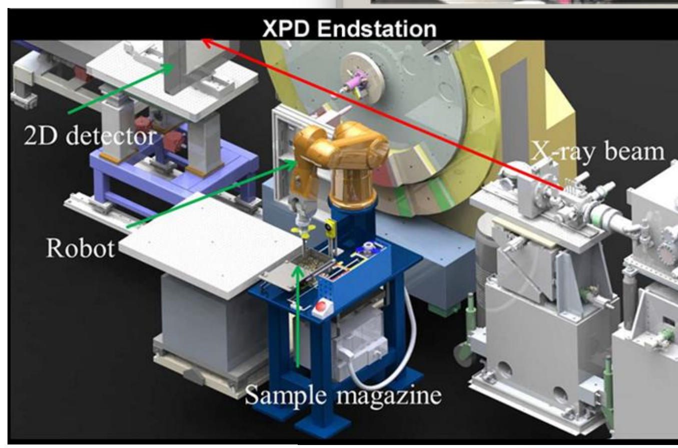


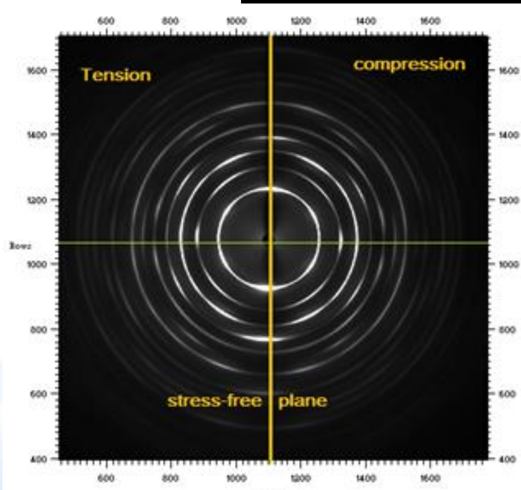


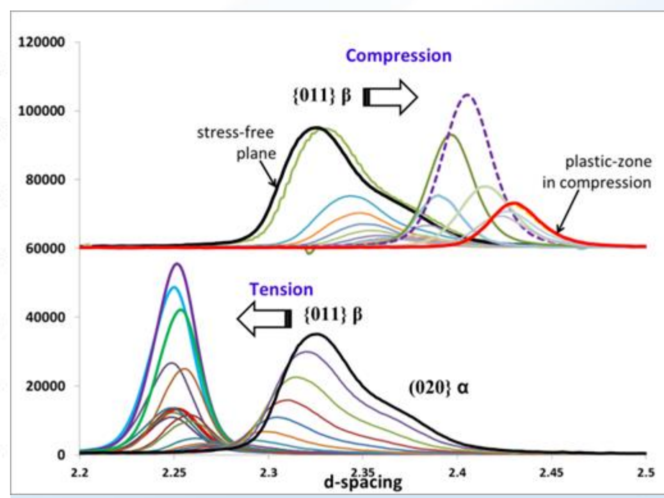
BNL Post-Irradiation Facilities X-ray Diffraction at NSLS II

Stage at NSLS II XPD Beamline









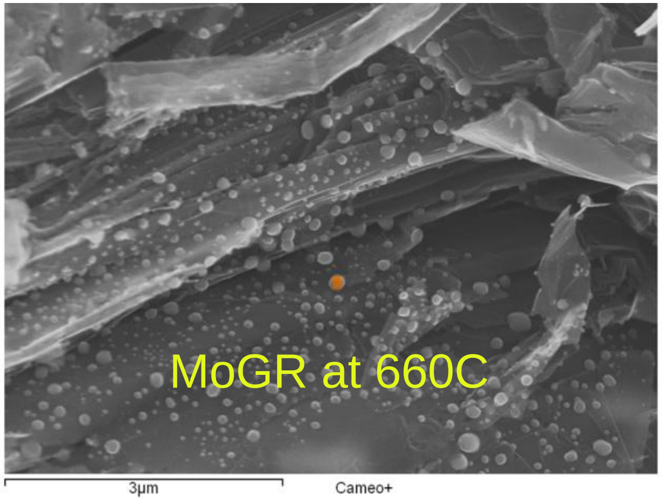
Characterization Studies/Capabilities at CFN

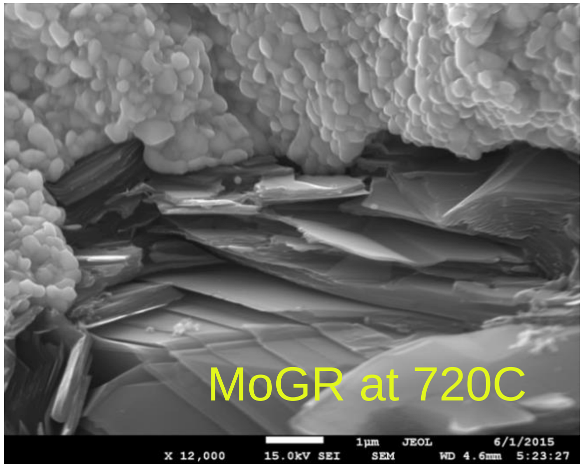
Unirradiated samples ONLY (to-date)

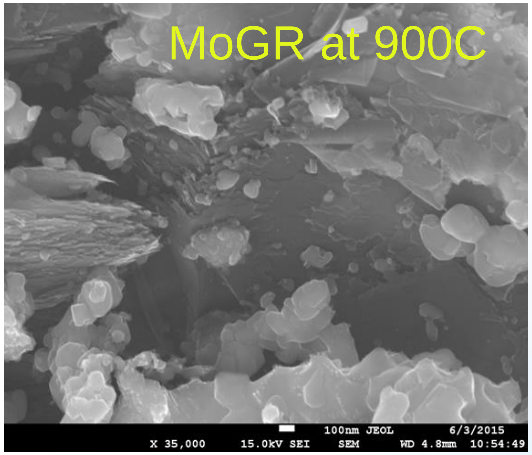
Studies:

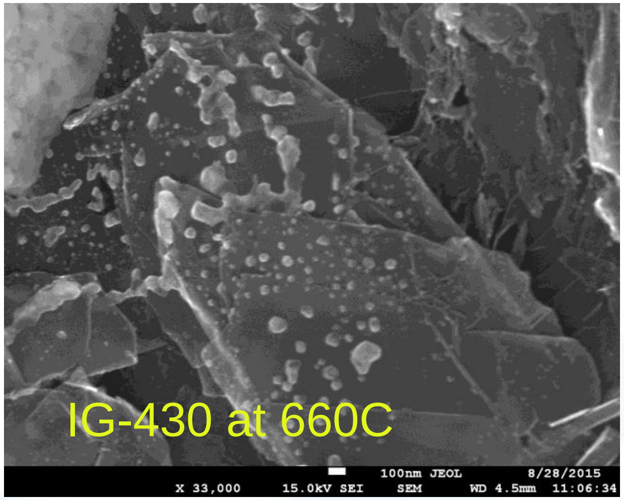
- **High Temperature Annealing**
- **DSC and TGA analysis**
- **FIB/TEM**
- **SEM with EDS/WDS**

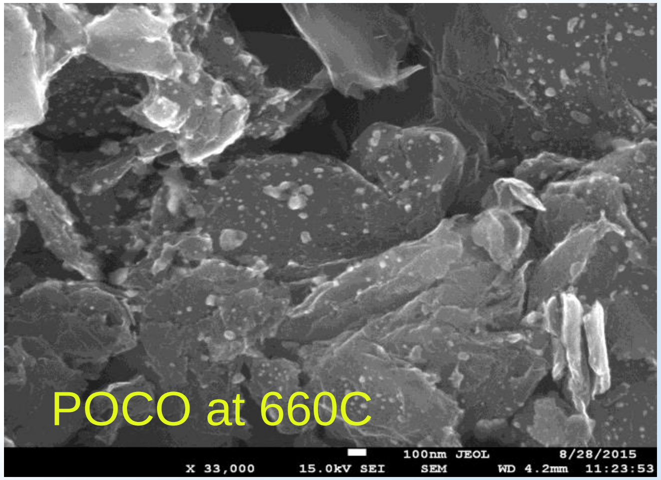
Characterization Studies/Capabilities at CFN



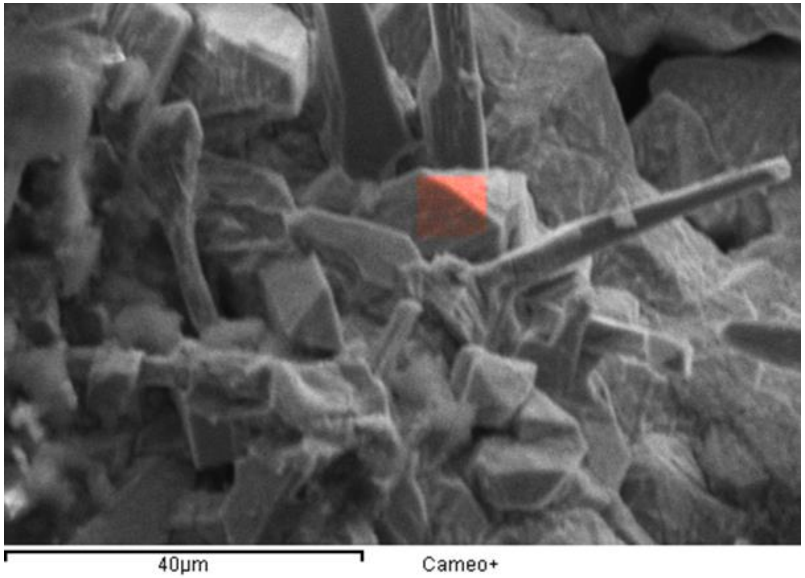


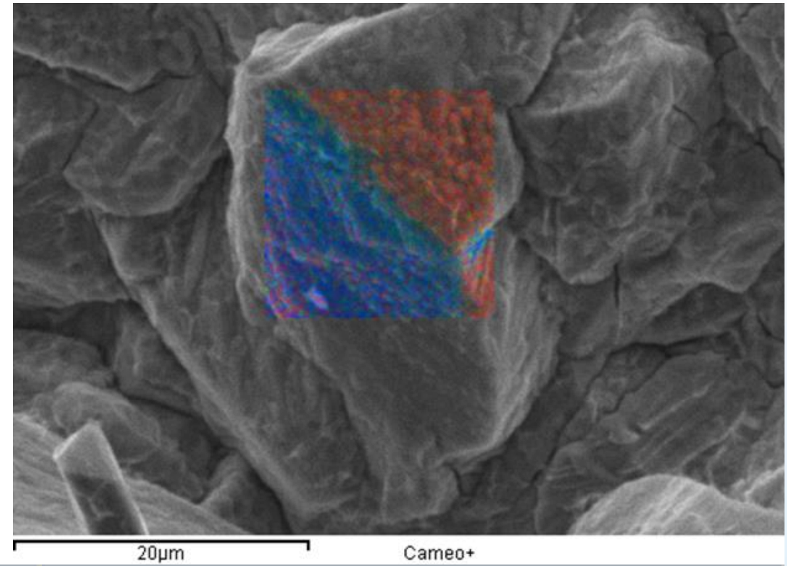


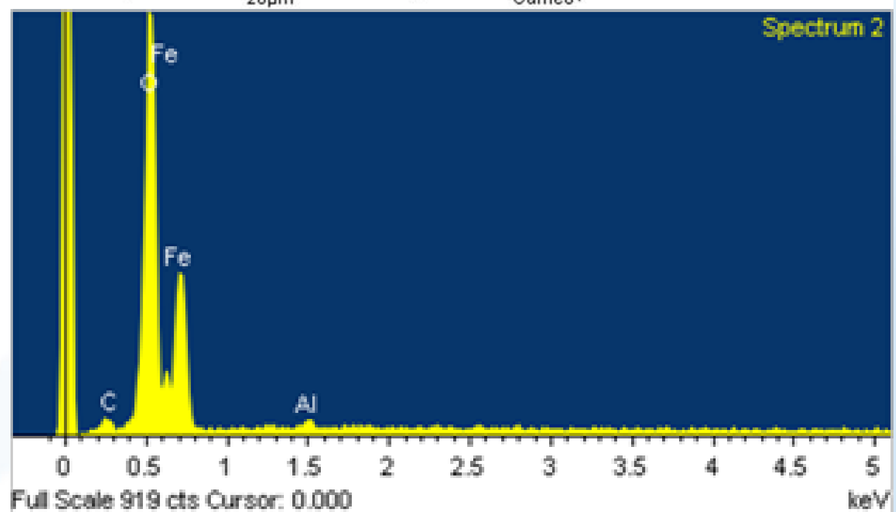




Characterization Studies/Capabilities at CFN

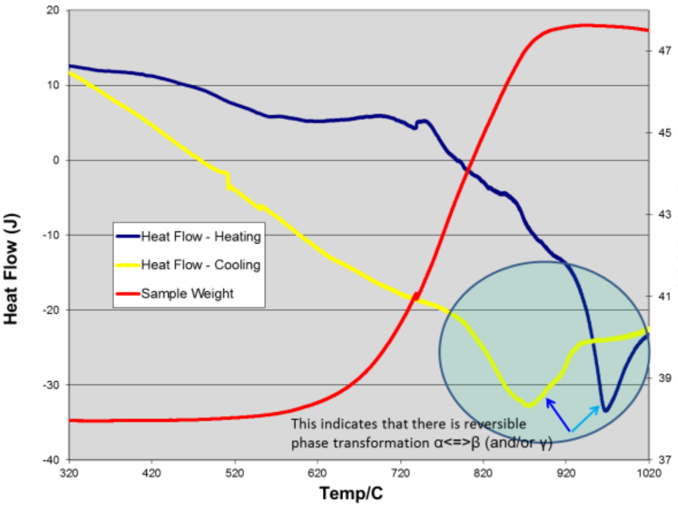


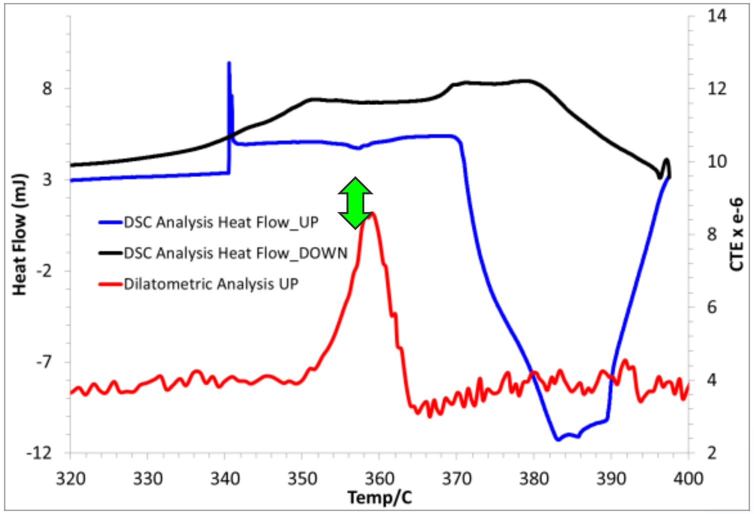


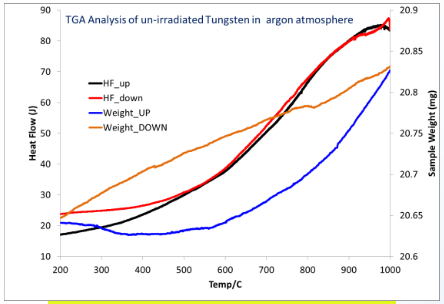


Element	Weight%	Atomic%
C K	2.47	6.96
O K	22.13	46.92
Al K	0.51	0.64
Fe K	74.90	45.48

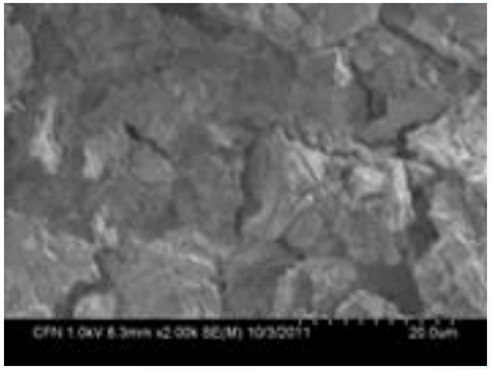
Thermo-mechanical Characterization W behavior (W ➔ WO_3) to temperatures reaching 1050 C

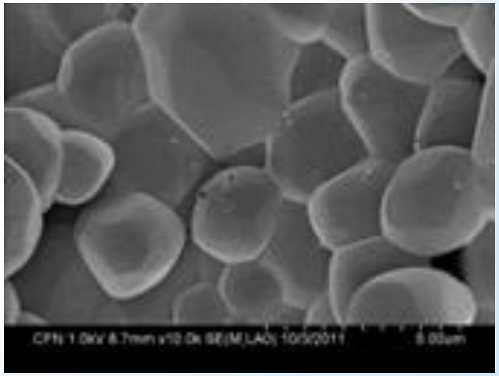


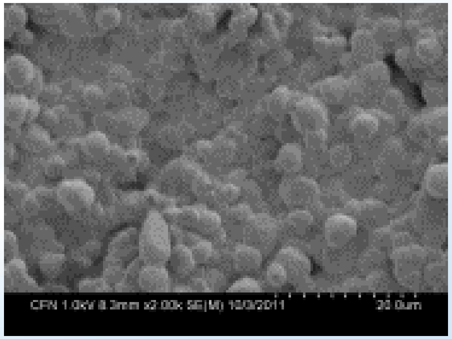


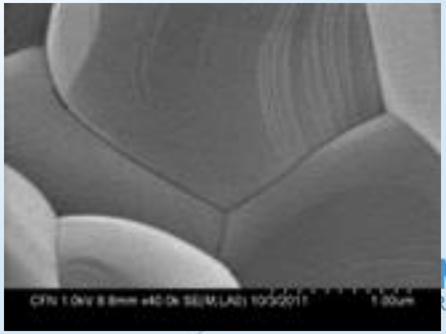


Asymmetry in weight gain/loss
Heat Flow asymmetry < 500 C









Evolution of W oxidation

Planned Experiment OBJECTIVE and CHALLENGES

Capsule:	1
Name:	Beryllium
Primary PI:	FNAL

Parameter	Value	Comments/Questions:
Peak Irradiation Temp Desired (°C):	400	May need insulating layer to get to this temperature?
Peak DPA Desired:	1	We understand that 0.1 is probably limit for this duration run
Peak He desired (appm):	3,000	Whatever occurs naturally is desired
Peak H desired (appm):	2,000	Whatever occurs naturally is desired
Expected atmosphere:	vacuum	

Sample Layer Index	Sample Material 1	Sample Material 2	Sample Geometry Type:	Layer Thickness (mm)	Number of samples	Interleaved with Layers:	PIE Test 1	PIE Test 2	PIE Test 3	PIE Test 4	PIE Test 5	PIE Question	Irradiation Question
1	Be S65H		PNNL or BNL mini-tensile	0.5	5	7	Tensile Pull	Microscopy (as needed)				Can 1.5 mm holes in PNNL mini-tensile design be used for compression test or other PIE (relatively low dose though)?	Do 1.5 mm holes in PNNL mini-tensiles need to be filled?
2	Be PF-60		PNNL or BNL mini-tensile	0.5	5	7	Tensile Pull	Microscopy (as needed)				What temperatures can tensile pulls be done at? Need rolling parameters from Materion	
3	Be S65H		PNNL or BNL mini-tensile	0.5	5	7	Tensile Pull	Microscopy (as needed)				Can PNNL geometry be lengthened so grips are in lower irradiation field?	
4	Be PF-60		PNNL or BNL mini-tensile	0.5	5	8	Tensile Pull	Microscopy (as needed)				Should these be tensile or bend tests? If bend, sample geometry?	With so many layers will the middle layers get too hot?
5	Be S65H	UHP Be 9999	PNNL or BNL mini-tensile	0.5	5	8	Tensile Pull	Microscopy (as needed)					
6	Be PF-60	UHP Be 9999	PNNL or BNL mini-tensile	0.5	5	8	Tensile Pull	Microscopy (as needed)					
7	Be S65H		Filler bar	1.5	4	1,2,3	Dim swelling	Conductivity	Microscopy, Micro-mechanic	Sonic velocity	CTE	Can CTE pull be done after micro-mechanics/FIB/etc? Is this thick enough for dilatometer?	
8	Be PF-60		Filler bar	1.5	4	4,5,6	Dim swelling	Conductivity	Microscopy, Micro-mechanic	Sonic velocity	CTE	Can the bar be polished prior to irradiation to aid microscopy and micro-mechanics?	
9	Be S65H		Disc Array	0.5	9		HiRadMat	Microscopy /Micro-mechanics				I envision (4) 1.5 cm dia discs with (5) 0.5 cm discs for micro-mechanics. Is 0.5 diameter discs too small for polishing?	
10	Be PF-60		Disc Array	0.5	9		HiRadMat	Microscopy /Micro-mechanics				Do these need to be discs? Square shape would be easier to fill gaps.	Gaps between discs need to be filled? Can they be filled with something Be-like? (but easier to machine)

Planned Experiment OBJECTIVE and CHALLENGES

Capsule:	2
Name:	Carbon
Primary PI:	FNAL

Parameter	Value	Comments/Questions:
Peak Irradiation Temp Desired (°C):	400	May need insulating layer to get to this temperature?
Peak DPA Desired:	1	We understand that 0.15 is probably limit for this duration run
Peak He desired (appm):	1,500	Whatever occurs naturally is desired
Peak H desired (appm):	1,500	Whatever occurs naturally is desired
Expected atmosphere:	vacuum	

	Sample Layer Index	Sample Material 1	Sample Material 2	Sample Geometry Type:	Layer Thickness (mm)	Number of samples	Interleaved with Layers:	PIE Test 1	PIE Test 2	PIE Test 3	PIE Test 4	PIE Test 5	PIE Question	Irradiation Question
	1	POCO ZXF-5Q		PNNL or BNL mini-tensile	1	5	5	Tensile Pull	Microscopy (as needed)				Grips may strip out. Does PNNL have clamp grips? Geometry?	
	2	POCO ZXF-5Q		PNNL or BNL mini-tensile	1	5	5	Tensile Pull	Microscopy (as needed)				What temperatures can tensile pulls be done at?	
	3	IG-430		PNNL or BNL mini-tensile	1	5	5	Tensile Pull	Microscopy (as needed)					
	4	Glassy Carbon		PNNL or BNL mini-tensile	1	5	5	Tensile Pull	Microscopy (as needed)				Should these be tensile or bend tests? If bend, sample geometry?	
This layer may be replaced by POCO/IG if C-C material is unavailable or not	5	C-C 3D		Filler bar	4	4	1,2,3,4	Dim swelling	Conductivity	Microscopy	Sonic velocity	CTE	Bend Test??	Do we have this material to test?

Planned Experiment OBJECTIVE and CHALLENGES

Capsule:	3
Name:	"S"
Primary PI:	CERN

Parameter	Value	Comments/Questions
Peak Irradiation Temp Desired	1000	
Peak DPA	1	
Peak He desired (appm):	?	
Peak H desired (appm):	?	
Expected atmosphere:	?	

	Sample Layer Index	Sample Material 1	Sample Material 2	Sample Geometry Type:	Layer Thickness (mm)	Number of samples	Interleaved with Layers:	PIE Test 1	PIE Test 2	PIE Test 3	PIE Test 4	PIE Test 5	PIE Question	Irradiation Question
	1	Si, mono		PNNL or BNL mini-tensile	0.5	5	5	Tensile Pull	Microscopy (as needed)					
	2	Si, poly		PNNL or BNL mini-tensile	0.5	5	5	Tensile Pull	Microscopy (as needed)					
	3	Si, mono		PNNL or BNL mini-tensile	0.5	5	5	Tensile Pull	Microscopy (as needed)					
	4	Si, poly		PNNL or BNL mini-tensile	0.5	5	5	Tensile Pull	Microscopy (as needed)					
	5	Si, mono	Si, poly	Filler bar	2	4	1,2,3,4	Bend					Bend geometry?	
	6	SiC		Bend	1	10		Bend						
This layer may be eliminated if J-PARC request not funded	7	SiC-SiC comp??		Bend	1	10		Bend					J-PARC request, not in proton budget yet!	
This layer may be eliminated if investigation of this effect at high dose is negative	8	Sapphire		Bar	0.5	10		Spectraphotometer					optical absorbtion/transmision. Who has this? Does effect saturate at high dose?	Can we pull out/replace capsules during run? This may mean separate capsule required for sapphire?